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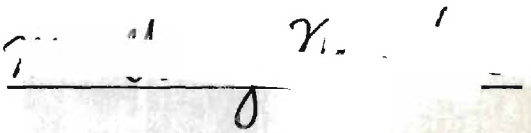

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THE KINETICS AND MECHANISM OF SOLVOLYSIS OF SOME PHOSPHATE ESTERS OF TERTIARY ALCOHOLS

A THESIS

Presented to

The Faculty of the Graduate Division

by

Melvin Gary Newton

In Partial Fulfillment

of the Requirements for the Degree

Doctor of Philosophy

in the School of Chemistry

Georgia Institute of Technology

July, 1966

THE KINETICS AND MECHANISM OF SOLVOLYSIS OF SOME PHOSPHATE ESTERS OF TERTIARY ALCOHOLS

Approved:

Date approved by Chairman: 20-X-66

This dissertation is respectfully dedicated

to my parents,

whose wisdom and guidance have made it possible.

ACKNOWLEDGMENTS

I sincerely thank Dr. James R. Cox, Jr. for suggesting the work presented herein. I am also grateful for his guidance, inspiration, and encouragement, not only in the pursuit of this thesis problem, but in all aspects of my graduate career.

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SUMMARY

The research described in this thesis was designed in part to establish the chemistry of the solvolysis of phosphate triesters of secondary and tertiary alcohols. Toward this purpose, tri-i-propyl and tri-t-butyl phosphates were synthesized and the rates of solvolysis determined. The alkaline solvolysis of tri-t-butyl phosphate in various ethanol-water solvents at 60°C. was first-order in ester over a wide range of hydroxide ion concentration. Solvolysis of the ester in 50% ethanol-water solution containing O^{18}-labeled water produced di-t-butyl phosphate containing no excess O^{18}. The mechanism is thus firmly established as a first-order rate-determining rupture of the carbon-oxygen bond to produce di-t-butyl phosphate and the t-butyl carbonium ion intermediate. The carbonium ion rapidly reacts with solvent to produce either t-butyl alcohol or ethyl t-butyl ether. The reaction mechanism is a close analogy to that of the t-butyl halides.

The rate data were correlated with the Grunwald-Winstein Y value, and the correlation was found to be linear over the entire solvent range of 40 to 90% ethanol-water. The value of m obtained, 0.467, was abnormally low for an S_N1 solvolysis. This low value was attributed to the poorer leaving ability of the di-t-butyl phosphate anion compared to the chloride ion.

The alkaline solvolysis of tri-i-propyl phosphate in water at 60°C. was extremely slow. At 90° in water, the reaction rate became fast enough to allow measurement of the rate of reaction. The hydrolysis was found

to be independent of the concentration of base and first-order in ester. Thus, the mechanism of solvolysis was shown to be similar to that of tri-t-butyl phosphate, i.e., rupture of the ester C-O bond to form the i-propyl cation and di-i-propyl phosphate. The extremely slow rate of hydrolysis reflects the large activation energy required in the ionization of the ester. The mechanisms of solvolysis of the series of esters, trimethyl, triethyl, tri-i-propyl, and tri-t-butyl phosphate are firmly established. Trimethyl and triethyl phosphates solvolyze with second-order kinetics by attack of hydroxide ion at phosphorus, displacing the alkoxide anion. The tri-i-propyl and tri-t-butyl esters are examples of a preliminary ionization mechanism, with C-O bond cleavage. The mechanisms and relative rates of the solvolysis of these esters are qualitatively similar to those of alkyl halides.

The alkaline solvolysis of triallyl phosphate was also studied and found to be first-order in base and first-order in ester. The point of cleavage was not determined.

Methyl pinacol phosphate, a five-membered ring phosphate triester, was synthesized and shown to solvolyze so rapidly in alkaline solution at 30°C. that a quantitative measure of the rate could not be determined. The products of hydrolysis were a mixture of approximately 80% ring-opened and 20% ring-closed diesters. The extremely fast rate of solvolysis accompanies all known five-membered ring phosphate esters. t-Butyl pinacol phosphate was synthesized also, but kinetic studies were not undertaken.

Because of our interests in the cause of the fast rates of solvolysis of five-membered ring phosphate esters, the crystal structure of methyl pinacol phosphate was determined by X-ray methods. Comparison of

the structure of the pinacol ester with the previously determined structure of methyl ethylene phosphate revealed essentially equivalent structural features except for a different positioning of the methyl ester groups. The methyl ester group in methyl ethylene phosphate is positioned over the ring; in methyl pinacol phosphate, the methyl group is rotated nearly 180° to a position over the phosphoryl group. This fact suggested considerable involvement of $d\pi$-$p\pi$ bond between the phosphorus and attached oxygen atoms.

By application of symmetry arguments, five-membered ring phosphate esters were found to approach an arrangement of phosphorus and oxygen atoms which allows only two $d\pi$-$p\pi$ bonds; non-cyclic phosphate triesters approach an arrangement which allows three $d\pi$-$p\pi$ bonds. The reduction of π-bonding in cyclic esters is suggested, in addition to ring strain, to account for the extremely fast rates of hydrolysis of these esters.

CHAPTER I

HISTORICAL BACKGROUND

Mechanisms of Phosphate Ester Solvolysis in Alkaline Solution

Generally, triesters of phosphoric acid hydrolyze rather rapidly in alkaline solution to produce the corresponding phosphate diesters; hydrolysis of the diesters is very slow in comparison.[1,2] This behavior usually yields easily to experimental investigation of mechanistic and reactivity differences in compounds. Although the rates and molecularities of hydrolysis of a large number of phosphate triesters are known, it is surprising that only triphenyl and trimethyl phosphate have been studied in mechanistic detail.

Trimethyl and triphenyl phosphate hydrolyze in water in the presence of base at a rate which is dependent on both ester and hydroxide ion concentration.[3] The rate of the trimethyl ester is only slightly depressed upon changing the solvent to 75% dioxane. The mechanism therefore involves both the ester and hydroxide ion in the transition state.

Three mechanisms are feasible on the basis of molecularity alone. Eq. 1 shows a simple nucleophilic displacement at carbon by hydroxide ion. A second possibility, shown in Eq. 2, is a direct nucleophilic displacement

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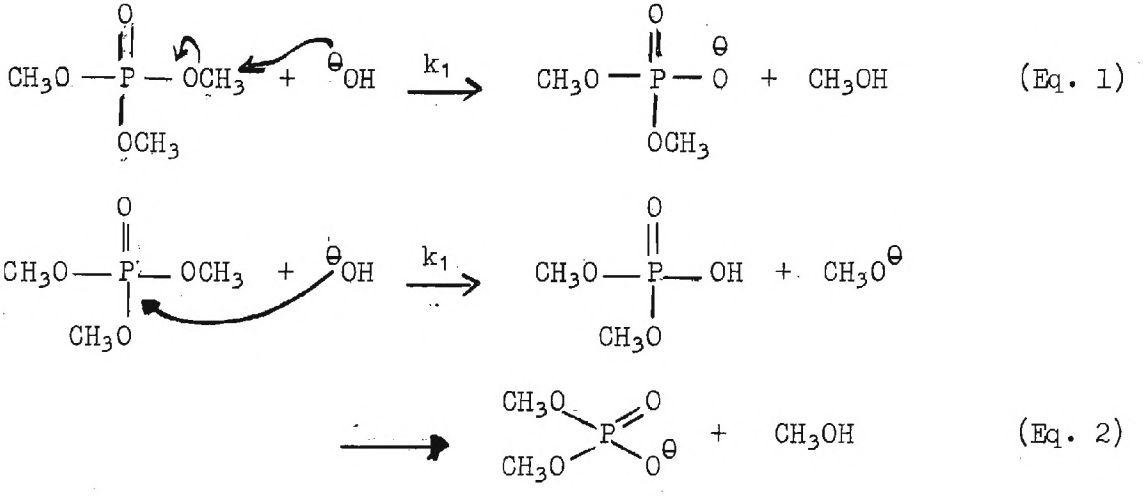
[1] J. R. Cox, Jr. and O. B. Ramsay, Chem. Rev., 64, 317 (1964).

[2] G. M. Kosalopoff, "Organophosphorus Compounds," John Wiley and Sons, Inc., New York, N. Y., 1950, p. 232.

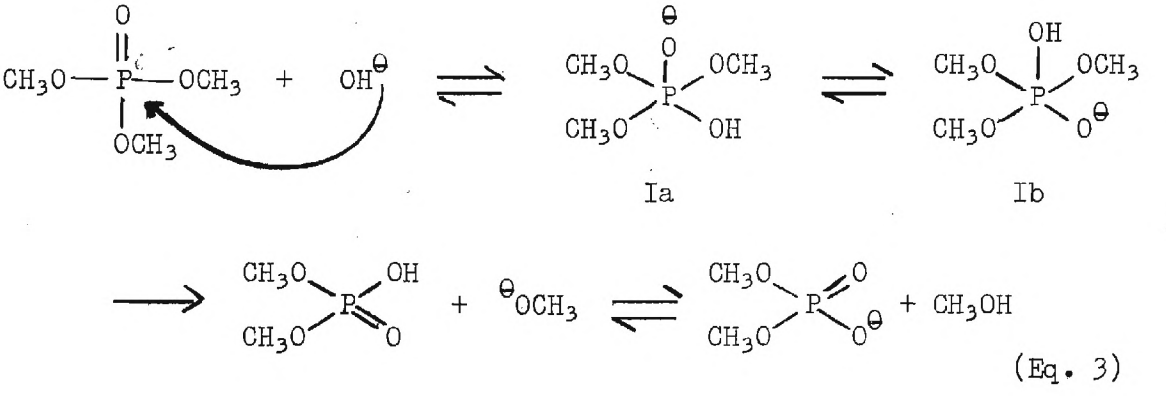
[3] P. W. C. Banard, C. A. Bunton, D. R. Llewellyn, C. A. Vernon, and J. A. Welch, J. Chem. Soc., 2670 (1961).

at phosphorus by hydroxide ion. The third mechanism which must be considered is an elaboration of Eq. 2, shown in Eq. 3; the involvement of a phosphoryl-hydroxide ion addition complex is postulated. This complex subsequently collapses to the products and is reminiscent of reaction of nucleophiles at carbonyl centers.



(Eq. 1)

(Eq. 2)



(Eq. 3)

The attack has been shown to occur at the phosphorus atom by O^{18} tracer studies.[3,4] Trimethyl phosphate solvolyzed in aqueous alkali containing excess O^{18} produced methanol of normal O^{18} content. Similar results were obtained with triphenyl phosphate. Phenol recovered from the hydrolysis

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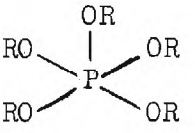
[4] E. Blumenthal and J. B. M. Herbert, Trans. Faraday Soc., 41, 611 (1945).

of triphenyl phosphate in alkaline aqueous solution with O^{18} enrichment showed no excess O^{18} label. These results firmly establish P-O cleavage in these esters.

No evidence has been advanced for the formation of an intermediate Ia,b in the solvolysis of phosphate triesters or derivatives, although pentaalkoxyphosphoranes, II, have been prepared and characterized.[5,6]



II

The available evidence has actually indicated that long-lived intermediates, such as Ia,b, are not formed in the course of solvolysis.[3,7] Unreacted trimethyl phosphate has been retrieved from a hydrolyzing solution of the ester in an aqueous, alkaline medium containing enriched H_2O^{18} and shown to have only normal O^{18} content. According to the mechanism of Eq. 3, a long-lived ester-hydroxide adduct would be expected to incorporate O^{18} into unreacted triester, since a long-lived intermediate should be able to exchange protons before returning to the reactants, assuming that the first step is reversible. Although the activation

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[5] F. Ramirez and N. B. Desai, J. Am. Chem. Soc., 85, 3252 (1963); F. Ramirez, O. P. Madan, N. B. Desai, S. Meyerson, and E. M. Banas, ibid., 85, 2681 (1963); F. Ramirez, N. Ramanathan, and N. B. Desai, ibid., 85, 3465 (1963).

[6] D. B. Denney and L. Soferstein, J. Am. Chem. Soc., 88, 1839 (1966); D. B. Denney and H. M. Relles, ibid., 86, 3897 (1964); D. B. Denney and S. T. D. Gough, ibid., 87, 138 (1965).

[7] I. Dostrovsky and M. Halmann, J. Chem. Soc., 1004 (1956).

energy for basic hydrolysis of triphenyl phosphate was significantly less than that of trimethyl phosphate, similar O^{18} exchange experiments revealed that no intermediate adduct was formed in the hydrolysis of this ester.[3] Table 1 records the rates, activation energies, and frequency factors for trimethyl, triethyl, and triphenyl phosphates. The mechanism for hydrolysis of triethyl phosphate is assumed to be attack at phosphorus by analogy to trimethyl phosphate.

Evidence for a five-coordinate phosphorus intermediate has been found in the reaction of benzyl phosphonium salts with hydroxide and alkoxide ions.[10] The kinetics of the reaction are third order overall with first-order dependence on the phosphonium salt and second-order dependence on hydroxide ion. The mechanism is thought to be addition of hydroxide ion to the positive phosphorus atom, forming a five-coordinate adduct which loses a proton to a second hydroxide ion. Finally, the intermediate anion collapses to the phosphine oxide and benzyl anion. The benzyl anion, in the presence of water, gives toluene. This scheme is shown in Eqs. 4-7. When an optically active phosphonium salt was used as the starting material, the phosphine oxide produced had the configuration inverted relative to that of the phosphonium salt.

The formation of the pentacoordinate phosphorus intermediate in the hydrolysis of phosphonium salts is aided by the full positive charge on the phosphorus atom and the instability of the benzyl leaving group. The major driving force in the reaction is very likely the formation of the phosphoryl bond. The stability of the phosphoryl bond is well

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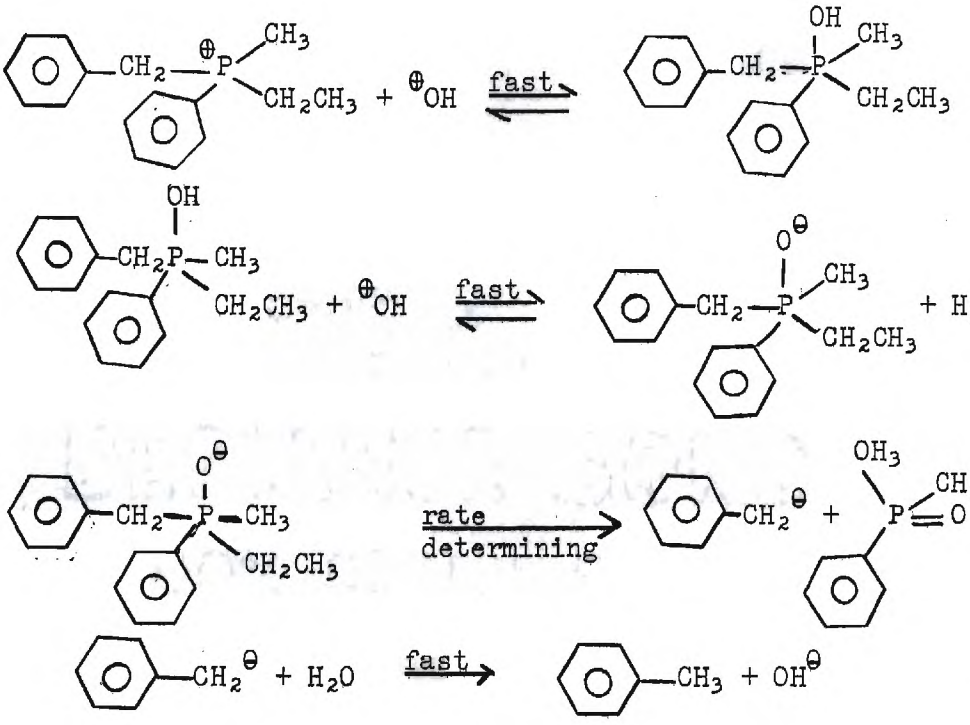
[10] M. Zanger, C. A. VanderWerf, and W. E. McEwen, J. Am. Chem. Soc., 81, 3806 (1959).

Table 1. Specific Rates of Reaction, Energies of Activation, and Frequency Factors for Trimethyl, Triethyl, and Triphenyl Phosphate.

Compound	Solvent	Temp. (°C)	k(mole/l.)$^{-1}$sec.$^{-1}$	ΔH (kcal/mole^{-1})	log pZ (l/mole sec.)	Ref.
$(CH_3O)_3PO$	H_2O	35	3.36×10^{-4}	16.2	8.1	3
"	75% dioxane	35	2.46×10^{-4}	----	---	3
$(CH_3CH_2O)_3PO$	H_2O	37.5	3.73×10^{-5}	15.0	6.16	8
"	50% dioxane	35	1.75×10^{-5}	14.9	5.8	9
$(C_6H_5O)_3PO$	60% dioxane	35	2.32×10^{-2}	10.2	4.9	3
"	75% dioxane	35	2.40×10^{-2}	----	---	3
"	75% ethanol	37.5	2.67×10^{-4}	16.1	13.57	8



established through estimates of its bond energy, which are quoted as 130-160 kcal./mole depending on the phosphoryl substituents.[11,12] It seems likely, therefore, that formation of pentacoordinate phosphorus intermediates would involve disruption of the phosphoryl bond with probable expenditure of much energy. The preferred lower energy pathway is the observed direct displacement of anions from phosphate derivatives.

Stereochemistry of Nucleophilic Substitution at Phosphorus

A variety of hybrid electronic states is possible in the phosphorus atom because of the involvement of phosphorus 3d orbitals in bonding schemes. A discussion of the hybridization states and stereochemical consequences of reaction at phosphorus has been recently reviewed by Green

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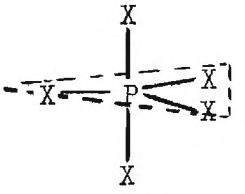
11 S. B. Hartley, W. S. Holmes, J. K. Jacques, M. F. Mole, and J. C. McCoubrey, Quart. Rev., 27, 204 (1963).

12 C. T. Mortimer, "Reaction Heats and Bond Strengths," Pergamon Press, New York, N. Y., 1962, Chap. 10.

and Hudson.[13]

Hybridization of 2s, $2p^3$, and $3d_{z^2}$ gives rise to a trigonal bipyramid, III, the geometry observed for PF_5, PCl_5, PCl_3F_2, and PBr_5 in the gas phase.[14] Approach of a nucleophile in forming the transition state



III

such as III, along the direction of either a radial bond or an axial bond can lead to inversion of configuration.[13,15] No choice may be made as to the entry point of a nucleophile at phosphorus with existing evidence. Quite possibly, the direction taken by the attacking group may depend on the electronic and steric factors of the specific compound. By analogy to carbon systems, approach of the nucleophile along the axial direction is preferred.

The square pyramidal structure, IV, has been demonstrated for pentaphenylphosphorane,[16] suggesting a hybrid of 2s, $2p^3$, and $d_{x^2-y^2}$ orbitals. Because this indicates that formation of square pyramidal structures is

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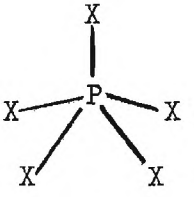
[13] R. F. Hudson and M. Green, Angew. Chem. Intern. Ed. Engl., 2, 11 (1963).

[14] Interatomic Distances. Chem. Soc. Special Publication No. 11, London, 1958, pp. M54 and M55.

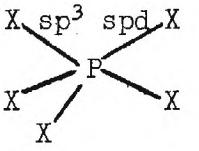
[15] P. C. Haake and F. H. Westheimer, J. Am. Chem. Soc., 83, 1102 (1961).

[16] P. J. Wheatley and G. Wittig, Proc. Chem. Soc., (London), 307 (1962).

energetically possible, inclusion of this hybridization state of phosphorus in discussion of transition state geometries is necessary. This structure in a transition state may lead to retention of configuration.[13,15]



IV



V

Reaction at bridgehead silicon atoms has been suggested to proceed through a transition state involving 2s, $2p^3$, and d_{xy} orbitals.[13] This transition state geometry allows the incoming group to approach at a rather acute angle to the departing group. (See structure V.) This arrangement has been termed "front-side attack." Although "front-side attacks" have not been observed in phosphorus chemistry, the possibility must be considered.

The stereochemical consequence of reaction of nucleophiles at phosphorus has been shown to be inversion of configuration in at least one case. Green and Hudson[17] have obtained direct proof of an inversion by comparing the rate of exchange of the methoxyl group labeled with C^{14}, of O-methyl ethylphenylphosphinate with methoxide ion, with the rate of racemization under the same conditions (Eq. 8). The labeled C^{14} methoxyl group, once removed, was effectively diluted by the solvent such that the reaction of Eq. 8 was irreversible. The rate of racemization of the

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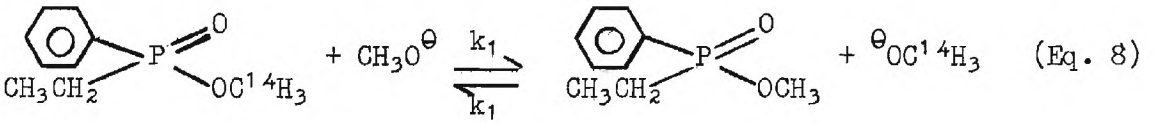
[17] M. Green and R. F. Hudson, Proc. Chem. Soc., (London), 307 (1962).

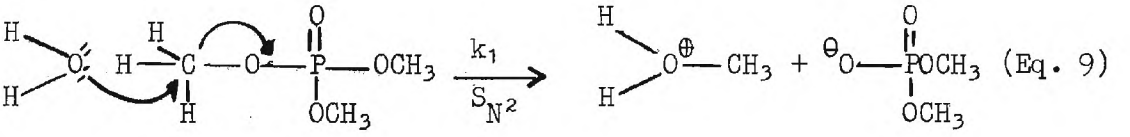
ester was twice that for loss of C^{14} methanol, showing that each substitution at phosphorus proceeds with inversion of configuration. Other work suggests that nucleophilic displacement in phosphate derivatives is often accompanied by inversion of configuration.[13]



(Eq. 8)

Mechanisms of Phosphate Ester Solvolysis in Neutral and Acidic Media

In contrast to the behavior of phosphate esters in alkaline solution, the neutral and acidic hydrolysis of these esters is quite slow. Trimethyl phosphate is the only ester which has been examined in mechanistic detail.[3] The reaction appears to be uncatalyzed by acid and proceeds by C-O cleavage as determined by O^{18} exchange studies. The mechanism of neutral and acidic hydrolysis, therefore, is an S_N2 displacement at carbon by water (Eq. 9).



(Eq. 9)

Comparison of the specific rate constants* for hydrolysis of triphenyl phosphate in alkaline solution (P-O cleavage, $k = 0.42$ sec.$^{-1}$) and in neutral solution (P-O cleavage, $k = 3 \times 10^{-9}$ sec.$^{-1}$) gives the relative nucleophilicity of water and hydroxide ion towards phosphorus.[3] From a ratio of the above rate constants, hydroxide ion, compared to

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* In 75% dioxane-water at 100°C. Rates estimated from the values of activation energy.

water, is a better nucleophile towards phosphorus by a factor of about 10^8. Attack at a saturated carbon atom has a corresponding ratio of about 10^4.[3] Therefore, in an ester which has a possibility for attack at carbon and phosphorus, hydroxide ion will tend to be selective for phosphorus, whereas water will prefer to attack tetrahedral carbon.

Substituent Effects on Phosphate Triester Reactivity

The reactivity of phosphate esters is markedly influenced by the nature of the displaced group.[1] Esters in which the leaving group is the anion of a strong acid, e.g., chloride ion, have large rate coefficients, and the rate of attack of neutral nucleophiles at phosphorus becomes significant. Phosphoryl halides for example, are readily hydrolyzed in water by attack at phosphorus.[7] As the displaced group becomes a stronger base, reactivity with hydroxide ion decreases and neutral nucleophiles tend to attack carbon in preference to phosphorus, as indicated in the neutral and acidic hydrolysis of trimethyl phosphate. Usually a gross change in the stability of the leaving group greatly influences the rate of hydrolysis. Such an effect is consistent with the presumed mechanism of the alkaline hydrolysis, i.e., direct displacement of the anion from phosphorus.

Both steric and electronic factors are important in determining phosphate ester reactivity and both must be considered when interpreting rate differences among phosphate esters. It is usually not possible to sort out each effect completely and, often, only the overall effect can be assessed.

According to Lucken and Whitehead,[18] a qualitative treatment of

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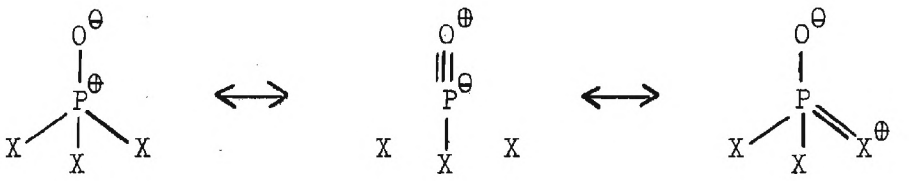
[18] E. A. C. Lucken, and M. A. Whitehead, J. Chem. Soc., 2459 (1961).

electronic factors can be deduced from a simple electronic picture of the bonding of the four groups attached to phosphorus in a phosphoryl derivative with three substituents. A phosphoryl trichloride molecule can be assumed to form a system of $\underline{\sigma}$ bonds to each substituent from the central phosphorus atom which is $\underline{sp^3}$ hybridized. Assume an orthogonal coordinate system in which the $\underline{z}$ axis lies along the phosphoryl bond and with the origin at phosphorus. The filled $\underline{p_x}$ and $\underline{p_y}$ orbitals on the oxygen atom are in a plane parallel to the xy-plane and coincide with the x and y axes, respectively. The phosphorus $\underline{d_{xz}}$ and $\underline{d_{yz}}$ orbitals have the correct symmetry for overlap with the oxygen $\underline{p_x}$ and $\underline{p_y}$ orbital pair. Overlap of these orbitals gives the phosphoryl group a triple bond character, VII, but charge transfer is far from complete and the main contributing form is the dipolar form, VI; the oxygen atom retains a net partial negative charge and the phosphorus atom remains relatively positive. In resonance language, the phosphoryl bond is best described as the hybrid of the canonical forms VI and VII, with VI as the largest contributor to the hybrid form.

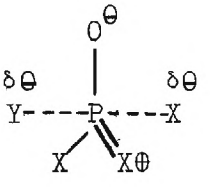
The remaining $\underline{d_{x^2-y^2}}$ and $\underline{d_{xy}}$ orbitals on phosphorus have the correct symmetry to form $\underline{d}$-$\underline{p}$ π bonds to each of the chlorine atoms, VIII, whereas the $\underline{d_{z^2}}$ orbital does not possess correct symmetry for overlap with the substituents. Thus the effect of substituents which are capable of $\underline{d}$-$\underline{p}$ π overlap is reduction of the positive character of phosphorus through $\underline{d}$-$\underline{p}$ π bonding.

Evidence presented earlier indicates that nucleophilic substitution at phosphorus is a direct, one-step process. A greater positive character on phosphorus increases the electrostatic attraction between



VI VII VIII

the electrophilic and nucleophilic centers, decreasing the activation energy of the nucleophilic substitution process. However, as pointed out by Cox and Ramsay,[1] a transition state, such as the one depicted in structure IX, is expected to be more polar than the reactants. A greater polarity in the phosphoryl group leads to an even greater polarity upon reaching the transition state. This increased polarity of the transition state then requires a greater ordering of solvent around it to disperse the charge, resulting in an entropy disadvantage. Thus, a substituent which forms weak π bonds to phosphorus increases the rate of attack of nucleophiles at phosphorus but suffers an entropy disadvantage upon reaching the transition state. Conversely, substituents which interact strongly with phosphorus d orbitals reduce the attraction between the ester and nucleophile, but require less solvent ordering in the transition state.

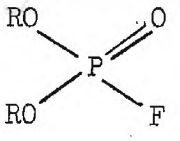


IX

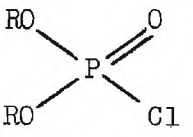
In a study of the association of phenol with various phosphoryl

derivatives, Aksnes[19] found a trend in the thermodynamic functions which supports this theory. An increase of the enthalopy of the association (hydrogen bond formation) resulted in a decrease of entropy.

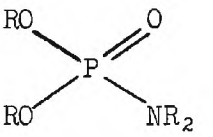
The effect of $d\pi$-$p\pi$ bonding can also be accommodated on the basis of the Lucken and Whitehead model, as discussed by Cox and Ramsay.[1] A fluorine substituent, for example, is capable of extensive overlap with phosphorus d orbitals. Experimentally, a phosphorofluoridate, X, hydrolyzes more slowly than the corresponding phosphorochloridate, XI, although the fluorine atom is more electronegative than the chlorine atom. The



X



XI



XII

chlorine substituent is thought to be relatively ineffective in forming π-bonds to phosphorus, in comparison to fluorine.

The nitrogen atom of a phosphoroamidate, XII, is capable of extensive overlap with phosphorus d-orbitals, thereby diminishing the partial charge on the phosphorus atom. Attraction of the nucleophile is reduced and, coupled with the instability of an amide leaving group, the amidates are relatively resistant to alkaline hydrolysis.

When sulfur replaces the oxygen atom in the phosphoryl group, the bond becomes less polar because of the difference in electronegativity of oxygen and sulfur. This is born out in the observation that phosphates

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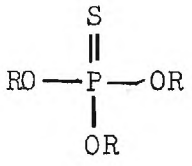
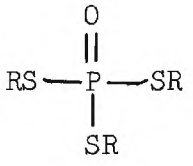
[19] G. Aksnes, Acta Chem. Scand., 14, 1475 (1960); G. Aksnes and G. Gramstat, ibid., 1485 (1960); G. Aksnes, ibid., 1515 (1960).

have larger dipole moments than the corresponding phosphorothioates.[7]



XIII



XIV

The phosphorus atom in phosphorothioates, XIII, is less positive than the phosphorus atom in the corresponding phosphate, reducing the rate of hydrolysis of the thioate compared to the phosphate ester. Replacement of sulfur for oxygen in the ester link greatly increases the rate of attack of nucleophiles at phosphorus. Sulfur, in comparison to oxygen, has a diminished ability to π-bond to phosphorus. The more positive phosphorus atom thus has an increased attraction for nucleophiles. The thiolates, XIV, hydrolyze faster than their oxygen analogs because of this effect and because mercaptide ion is a better leaving group than alkoxide.

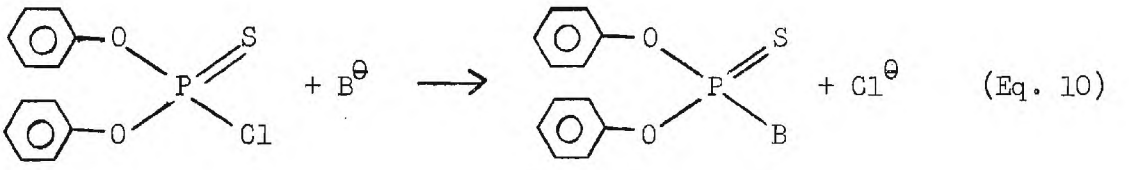
Successive replacement of the hydrogen atoms on the α-carbon atom of the esterifying alcohol with bulkier groups causes the rate of attack of nucleophiles at phosphorus to be greatly slowed due to a steric blocking of the central phosphorus atom by these substituents. The specific rate constant of the alkaline hydrolysis of trimethyl phosphate in water at 35°C is 3.36×10^{-4} lit/mole-sec. This is reduced in triethyl phosphate to 3.73×10^{-5} lit/mole-sec., a factor of about 10. The compounds listed in Tables 2 and 3 indicate further evidence of steric inhibition of phosphate ester hydrolysis. Extension of the straight chain has little effect; the greatest single effect occurs when ethyl is substituted for methyl. Branching at the α-carbon atom induces large rate inhibitions

but branching at the β-carbon apparently has only a slightly greater effect than substitution at the end of a straight chain.

Nucleophilicity toward Phosphoryl Phosphorus

A phosphoryl triester is normally inert to most nucleophiles, except oxygen anions, unless the leaving group is the anion of a strong acid. Esters not possessing the required leaving group usually are attacked by nucleophiles at carbon rather than at phosphorus.[1] Usually, the attacking nucleophile must be a stronger base than the leaving group to achieve a displacement reaction at phosphorus.

Miller[20] has studied the relative rates of reaction of a number of oxygen and sulfur anions with O,O-diphenyl phosphorochloridothioate (Eq. 10). The logarithm of the observed rate constant for each of these anions is plotted against the pK_a of the conjugate acid of the anion in Fig. 1. The correlation of the rate of reaction with the base strength of the anions is remarkable in that no apparent distinction is made between oxygen and sulfur anions. Thus, the base strength of an anion appears to be a good measure of the nucleophilicity of this anion toward phosphorus.



(Eq. 10)

However, nucleophiles which have an electronegative atom with unshared electrons adjacent to the attacking atom exhibit greater

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[20] B. Miller, J. Am. Chem. Soc., 82, 3924 (1960); ibid., 84, 403 (1962).

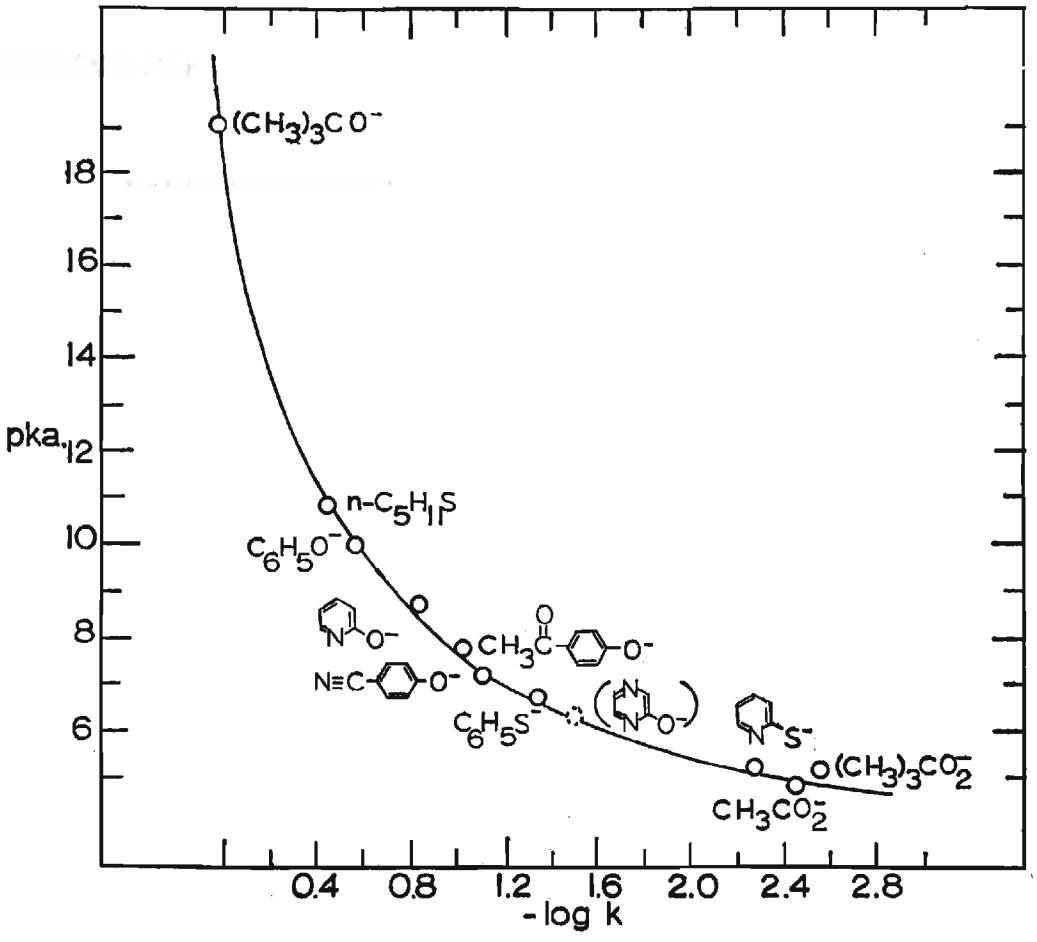
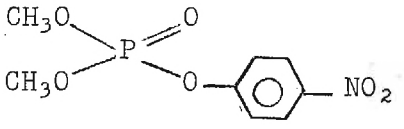
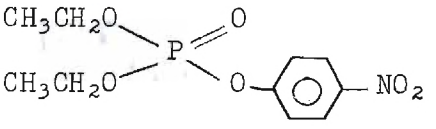
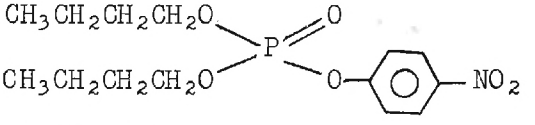
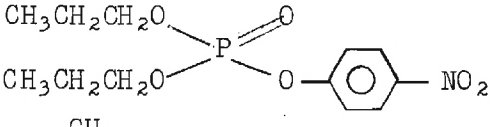
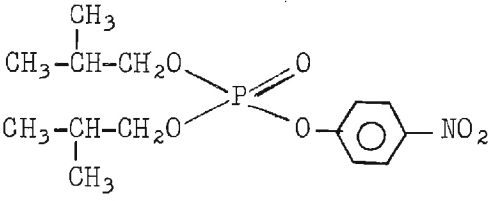
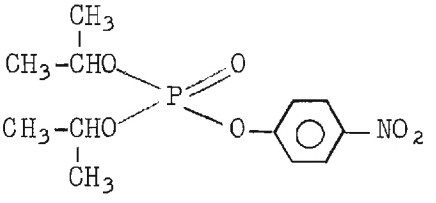
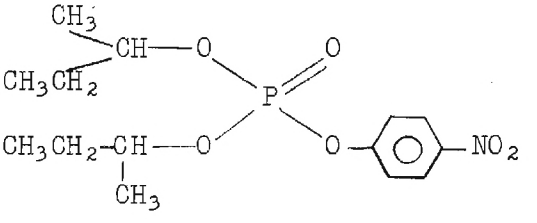


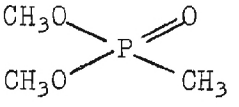
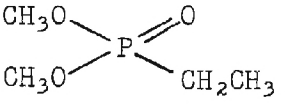
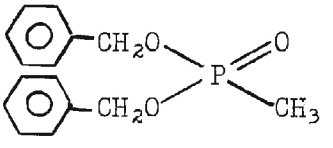
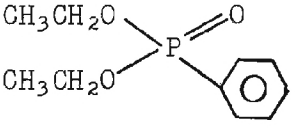
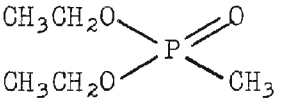
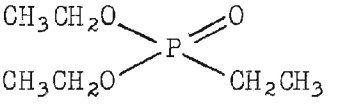
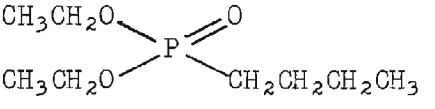
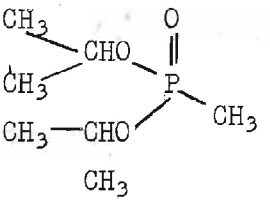
Fig. 1. A Plot of the Logarithm of the Rate of Reaction of Anionic Nucleophiles with O,O-Diphenylphosphorochloridothioate *versus* pK_a of the Conjugate Acid of the Anion.

Table 2. Specific and Relative Rates of Alkaline Hydrolysis of Some p-Nitrophenyl Phosphates.

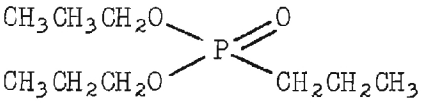
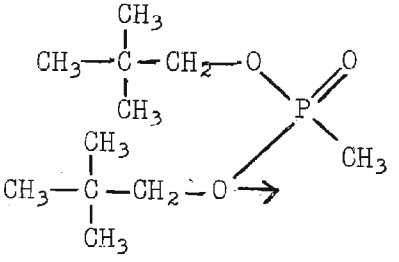
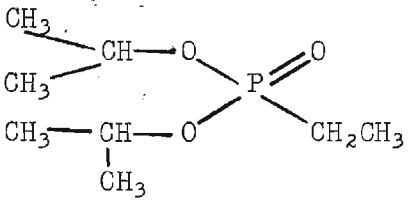
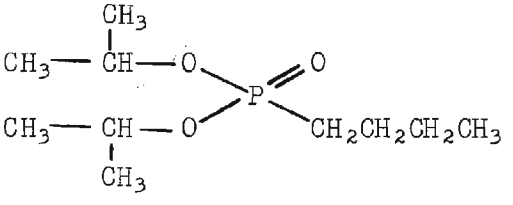
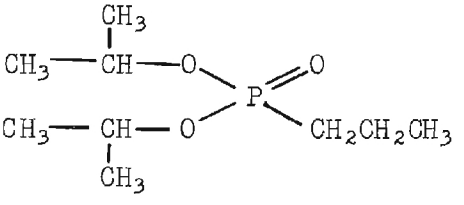
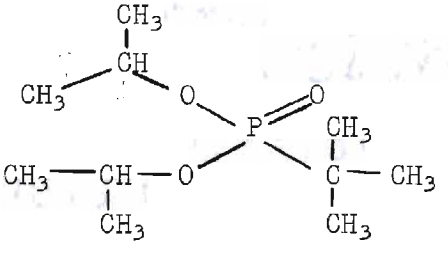
	k_1 ($l \cdot mole^{-1} sec.^{-1}$)* H_2O, 37°C.	Relative Rate
	8.8×10^{-2}	100.0
	2.67×10^{-2}	30.4
	1.8×10^{-2}	20.4
	1.67×10^{-2}	19.0
	1.46×10^{-2}	16.6
	2.5×10^{-3}	2.8
	1.22×10^{-3}	1.4

* Data taken from Ref. 1.

Table 3. Specific and Relative Rates of Alkaline Hydrolysis of Some Phosphonate Derivatives.

	k_1 ($l.mole^{-1}$ $sec.^{-1}$)* H_2O, 100°C.	Relative Rate
	2.35×10^{-1}	100,000
	1.43×10^{-1}	60,000
	5.9×10^{-2}	25,100
	3.75×10^{-2}	15,900
	1.80×10^{-2}	7,600
	9.40×10^{-3}	4,000
	2.05×10^{-3}	872
	4.82×10^{-4}	205

* Data taken from Ref. 1.

	4.60×10^{-4}	196
	2.25×10^{-4}	96
	8.67×10^{-5}	37
	1.51×10^{-5}	6
	5.0×10^{-6}	2
	$< 4.16 \times 10^{-6}$	< 2

nucleophilicity than is predicted from their basicities. This has been termed "α effect"[21] and has been suggested to arise from the greater electron availability for bond formation. The possibility of bifunctional catalysis has not been excluded.[20]

Hudson and Harper[22] have shown that hydroxide ion is about 1000 times more reactive towards a series of phosphate esters than predicted from its redox potential.[22,23] It was concluded that water as well as chloride, bromide, thiocyanate, iodide, and thiosulfate anions, which react at the predicted rate, attack carbon, whereas hydroxide ion substitutes at phosphorus. This has been shown to be the case for water and hydroxide ion in trimethyl phosphate.[3]

Reactivity of Five-membered Ring Phosphate Triesters

It has been known for some time that phosphate di- and triesters which possess a hydroxyl function adjacent to the esterified hydroxyl group are much more reactive than esters not possessing this function. Occurrence of this behavior was first observed in biological systems. Thus, ribonucleic acid is rapidly depolymerized under mild alkaline conditions to a mixture of 2'- and 3'-nucleotides, Eq. 11, whereas desoxyribonucleic acid, which does not possess a β-hydroxyl function, is relatively stable under similar conditions.[24] l-Glyceryl phosphate, XV, is

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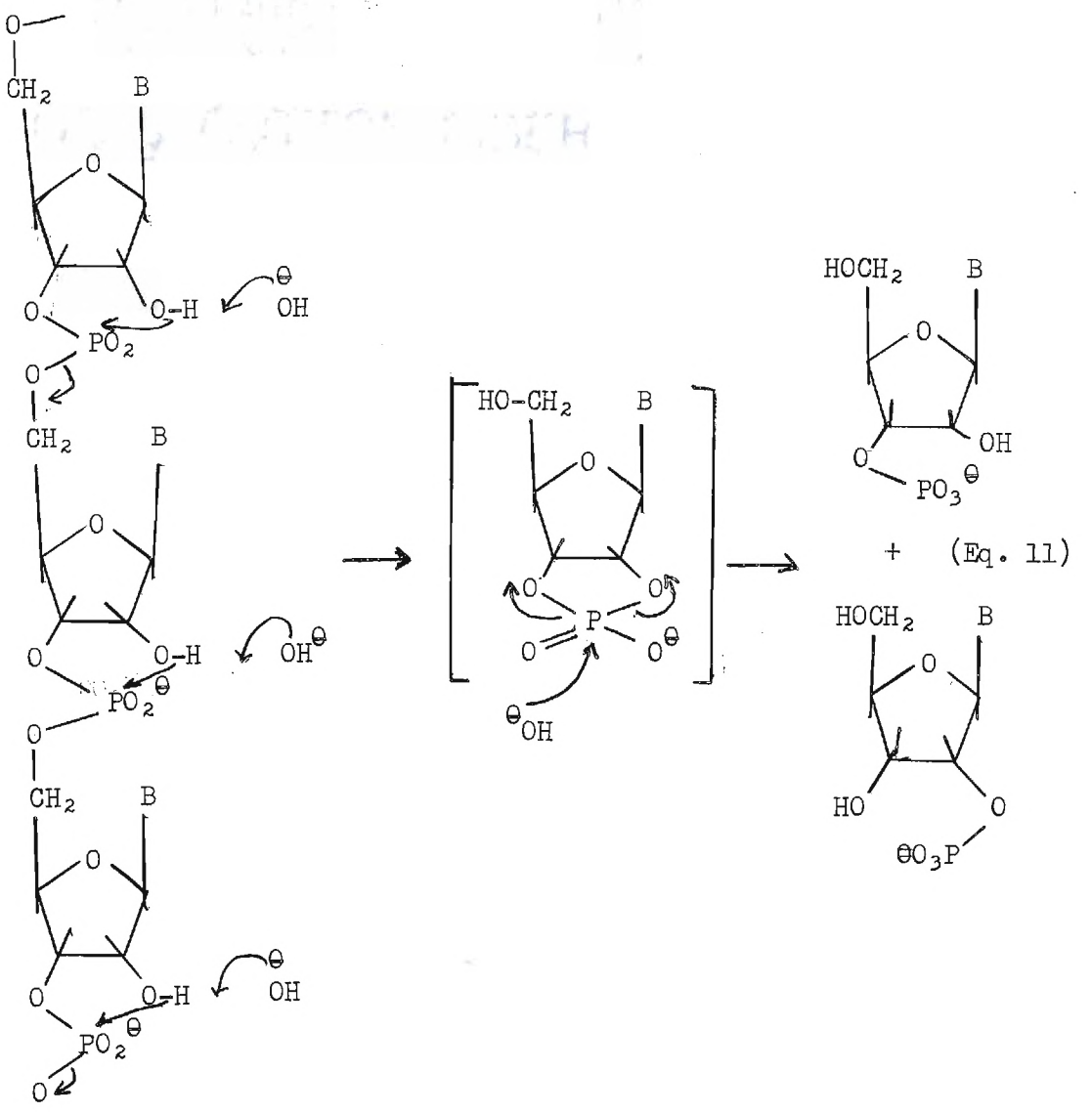
21 J. O. Edwards and R. G. Pearson, J. Am. Chem. Soc., 84, 16 (1962).

22 R. F. Hudson and P. C. Harper, J. Chem. Soc., 1356 (1958).

23 J. O. Edwards, J. Am. Chem. Soc., 76, 1540 (1954).

24 R. Markham and J. D. Smith, Biochem. J., 52, 552 (1952); ibid., 558 (1952).



+ (Eq. 11)

stable in base but methyl 1-glyceryl phosphate, XVI, has been found to solvolyze rapidly under these conditions to a mixture of 1- and 2-glyceryl phosphates. Similarly, while methyl 2-methoxyethyl phosphate, XVII, is quite resistant to hydrolysis in the presence of base, methyl 2-hydroxyethyl phosphate, XVIII, is rapidly hydrolyzed under the same conditions to 2-hydroxyethyl phosphate, XIX.[26] The effect is not limited to

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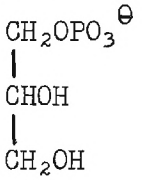
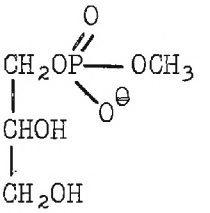
[26] O. Bailly and J. Gaume, Bull. soc. chim., France, [5] 3, 1396 (1936).

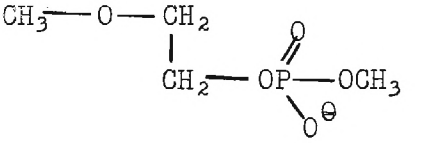
diesters. The triester, dimethyl 2-methoxyethyl phosphate is converted by base to methyl 2-methoxyethyl phosphate which is quite inert to further hydrolysis, Eq. 12.[26] However, dimethyl 2-hydroxyethyl phosphate in the presence of base is ultimately hydrolyzed to 2-hydroxyethyl phosphate, Eq. 13.



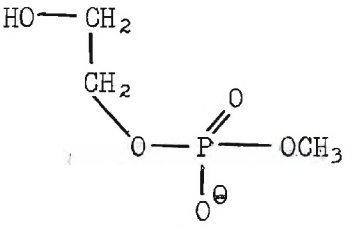
XV



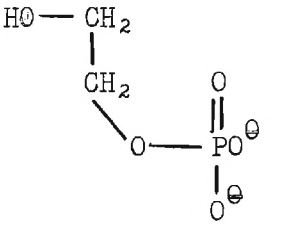
XVI



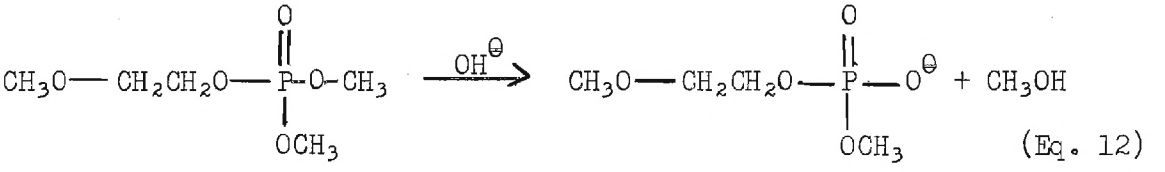
XVII



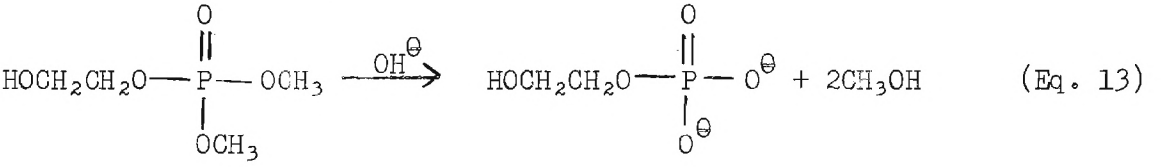
XVIII



IX



(Eq. 12)



(Eq. 13)

Fono[27] and, later, Brown and Todd[28] proposed formation of cyclic

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27 A. Fono, Arkiv. Kemi, 24A, No. 34, 14 (1947).

28 D. M. Brown and A. R. Todd, J. Chem. Soc., 52 (1952).

five-membered ring phosphate esters as intermediates which were subsequently and rapidly hydrolyzed. The demonstration by Chargaff[29] that the establishment of equilibrium between 1- and 2-glycerophosphates in acid is intramolecular strengthened this proposal. The isolation of five-membered ring esters[24] and the demonstration that they are hydrolyzed by base rapidly enough to fit the proposed scheme[30] essentially proved the involvement of the proposed intermediates in the hydrolytic scheme. Lipkin, Talbert, and Cohn[31] found that the alkaline hydrolysis of ribonucleic acid in H_2O^{18} proceeds with the introduction of only one atom of O^{18} in the phosphate group of the nucleotides produced. This suggested exclusive P-O bond cleavage.

Generally, the evidence presented above indicated that a β-hydroxyalkyl phosphate di- or tri-ester hydrolyzes by the following mechanism:

1) Hydroxide ion removes the proton of the β-hydroxyl function, producing an alkoxide ion, Eq. 14.
2) The alkoxide ion attacks the neighboring phosphorus atom with direct expulsion of the departing group and formation of a five-membered ring intermediate, Eq. 15. The favorable activation energy for this process presumably is due to the entropy advantage of two reacting centers held closely together by the structural features of the molecules.
3) The five-membered ring ester is rapidly hydrolyzed to the

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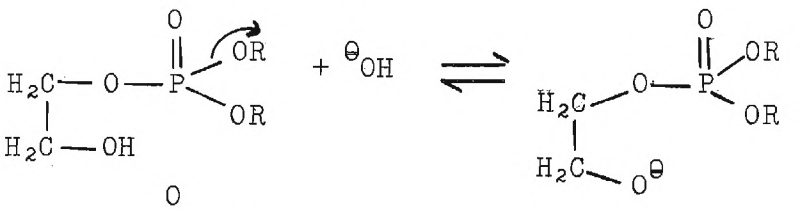
29 E. Chargaff, J. Biol. Chem., 144, 455 (1942).

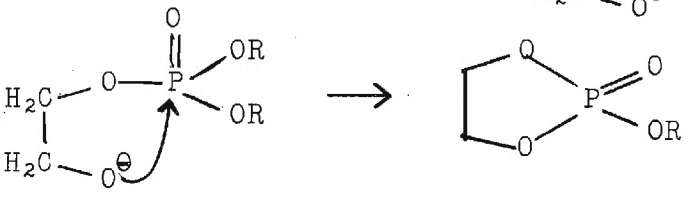
30 D. M. Brown, D. I. Magrath, and A. R. Todd, J. Chem. Soc., 2708

31 O. Lipkin, P. T. Talbert, and M. Cohn, J. Am. Chem. Soc., 76, 2871 (1954).

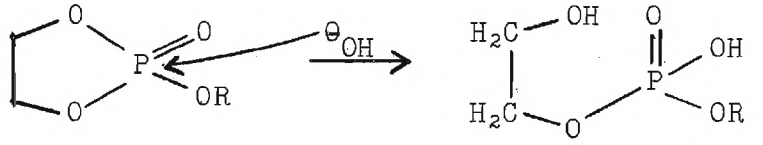
final products, with ring P-O cleavage, Eq. 16.



(Eq. 14)

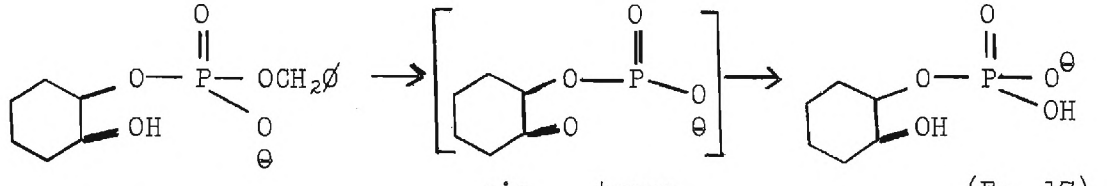


(Eq. 15)



(Eq. 16)

Brown and coworkers have focused attention on the first steps of the sequence, the transesterification, Eqs. 14 and 15. They found that benzyl-*cis*-2-hydroxycyclohexyl phosphate reacts in alkaline solution about 6.6 times faster than the *trans*-isomer to produce benzyl alcohol and 2-hydroxycyclohexyl phosphate, Eq. 17.[32] The conformation of the



cis *trans* (Eq. 17)

six-membered ring with the two hydroxyl groups *cis*-, *i.e.*, one axial and one equatorial, is more favorable for ring closure than that of the trans-isomer, where both groups are presumably equatorial. The rate-limiting step in each case was found to be ring closure in contrast to the

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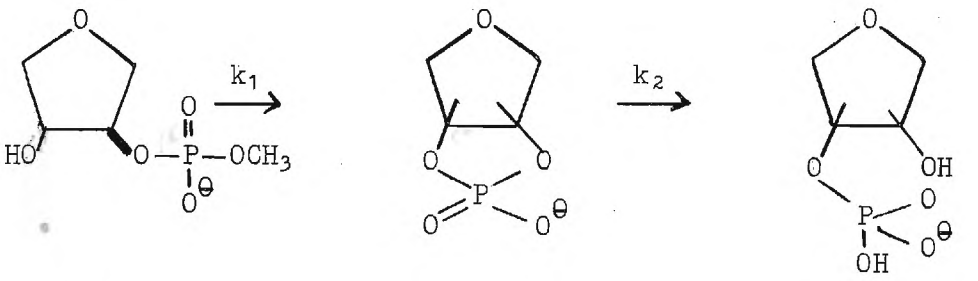
[32] D. M. Brown and M. Higson, *J. Chem. Soc.*, 2034 (1957).

hydrolysis of ribonucleic acid in which ring opening was shown to be slower than ring closure. Presumably, the cis arrangement of the β-hydroxyl function in a five-membered ring is more favorable for ring closure than either the cis- or trans-isomers of the cyclohexane ring. Evidence supporting this view has been presented by Guida[33] who prepared both the cis-3-hydroxy-4-tetrahydrofuranyl methyl phosphate, XX, and cis-3,4-tetrahydrofuranyl cyclic phosphate, XXI. Hydrolysis of each of these esters in base yielded the phosphate dianion, XXII. Structure XX cyclizes in base to XXI, which opens the ring to produce XXII. The determination of the rate of hydrolysis of each compound showed that ring closure (k_1) proceeds at a rate which is about twice that of ring opening (k_2). This behavior is similar to the behavior of ribonucleic acid, and does indicate that formation of five-membered ring esters is slightly favored when the



XX XXI XXII

two neighboring hydroxyl functions are present in a cis-arrangement on a five-membered ring.

Westheimer and coworkers have examined the solvolysis of the extremely labile five-membered ring phosphate intermediates in detail, concentrating principally on the ethylene phosphate nucleus. Kumamoto, Cox,

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[33] J. H. Guida, Masters Thesis, Georgia Institute of Technology, 1964.

and Westheimer[34] have determined the rates of alkaline and acid hydrolysis of ethylene phosphate. In both acid and base, the cyclic phosphate solvolyzed about 10^7 times faster than dimethyl phosphate. As determined by O^{18} exchange experiments, ethylene phosphate solvolyzed in alkaline solution with exclusive P-O cleavage.[15] However, dimethyl phosphate was predominantly attacked by hydroxide at the methyl carbon and only about 10% of the hydrolysis occurred with P-O cleavage. Thus, attack of hydroxide at phosphorus was approximately 10^8 times faster in the cyclic ester compared to the non-cyclic ester. This unusually large rate enhancement apparently accompanies all reported five-membered cyclic phosphate di- and tri-esters,[35,36,37] and a similar rate enhancement has been reported for the five-cyclic phosphonate ester, propyl phostonate.[38] Compared to sodium ethyl ethylphosphonate, lithium propylphostonate hydrolyzes about 5×10^4 times faster in acid and about 6×10^5 times faster in alkaline solution. The propylphostonate hydrolyzes with exclusive P-O cleavage, whereas ethyl ethylphosphonate hydrolyzes with about 50% C-O and 50% P-O cleavage. Rate enhancements have also been found in cyclic sulfate esters.[39]

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34 J. Kumamoto, J. R. Cox, Jr., and F. H. Westheimer, J. Am. Chem. Soc., 78, 4858 (1956).

35 J. R. Cox, Jr., R. E. Wall, and F. H. Westheimer, Chem. Ind. (London), 929 (1959).

36 H. G. Khorana, G. M. Gener, R. S. Wright, and J. G. Moffatt, J. Am. Chem. Soc., 79, 430 (1957).

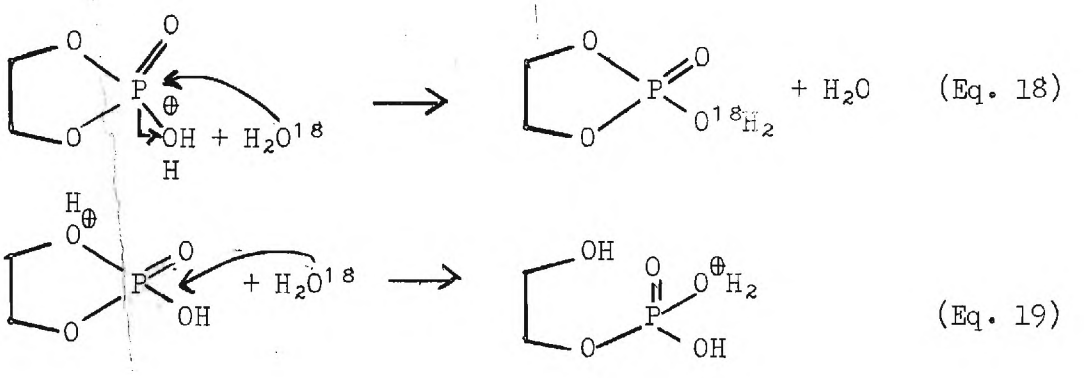
37 T. R. Fukoto and R. L. Metcalf, J. Medicin. Chem., 8, 759 (1965).

38 A. Eberhard and F. H. Westheimer, J. Am. Chem. Soc., 87, 253 (1965).

39 E. T. Kaiser, M. Panar, and F. H. Westheimer, J. Am. Chem. Soc., 85, 602 (1963).

By comparing the heats of alkaline hydrolysis of methyl ethylene phosphate and dimethyl 2-hydroxyethylphosphate, Cox, Wall, and Westheimer[35] found the cyclic ester to be less stable than the acyclic ester by approximately 5.5 kcal/mole. This energy was attributed to ring strain in the cyclic ester and furthermore, relief of this strain upon reaching the transition state could contribute to the rate enhancement. The six-membered ring phosphate ester, trimethylene phosphate, solvolyzes at a rate which is approximately the same as that of dimethyl phosphate, and the seven-membered ring hydrolyzes somewhat slower.[36,40]

Insight into the nature of the transition state of hydrolysis of these cyclic five-membered ring esters was gained through the discovery that O^{18} exchange into the phosphoryl oxygen occurred in the acid-catalyzed hydrolysis of ethylene phosphate.[15] The O^{18} exchange reaction is accelerated by approximately the same factor as the hydrolysis. Relief of strain thus apparently accompanies both hydrolysis and exchange in the transition state. Eq. 19 depicts the exchange reaction which is essentially displacement of water for water. The hydrolysis reaction is shown



40 E. Cherbuliez, H. Probst, and J. Rabinowitz, Helv. Chim. Acta, 42, 1377 (1959).

in Eq. 19. Assuming that the transition state geometry for hydrolysis and exchange is a trigonal bipyramid, two possibilities are allowed. Structures XXIIIa and XXIIIb demonstrate one possibility, namely, that the entering and departing groups occupy axial positions. The transition state for exchange, XXIIIa, expands the preferred ring OPO angle to 120°, whereas the transition state for the hydrolysis contains a ring OPO angle of 90°. It is difficult to see how both expansion and contraction of the preferred tetrahedral OPO angle in the ground state could relieve strain in the transition state for both hydrolysis and exchange; thus structures XXIIIa and XXIIIb represent an improbable geometry for the transition states.

A geometry in which entering and departing groups occupy basal positions of the trigonal bipyramid is shown in structures XXIVa and XXIVb. The ring OPO angle is contracted to 90° in both cases and would correspond to similar energies in both hydrolysis and exchange. Thus, XXIVa and XXIVb represent likely transition state geometries for exchange and hydrolysis, respectively. However, the square pyramidal geometry, XXVa and XXVb, represent a similar situation and cannot be ruled out on the basis of existing evidence. Usher, Dennis, and Westheimer[41] have calculated the minimized bond angle and eclipsing strain in cyclic systems based on a planar model of the ring. On the basis of these calculations, reduction of the ground state OPO angle from a preferred tetrahedral angle of 109.5° to 90° in the transition state does reduce the strain energy of the system. Increase of the OPO angle to 120°

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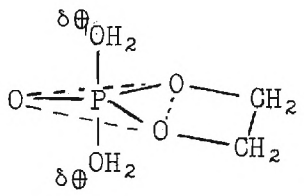
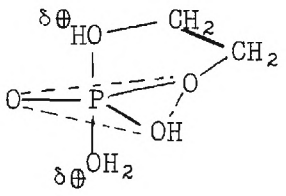
[41] D. A. Usher, E. A. Dennis, and F. H. Westheimer, J. Am. Chem. Soc., 87, 2320 (1965).

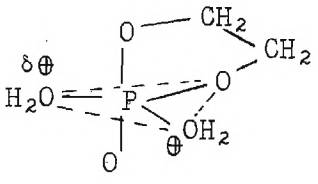
is accompanied by a large increase of strain energy. The five-membered ring in the pentaalkoxyphosphorane, XXVI, has been shown by X-ray structural determination to occupy the axial and basal positions[42] and lends support to the postulated decrease of the OPO ring angle to 90° in the transition state.. Furthermore, the OPO ring angle in methyl ethylene



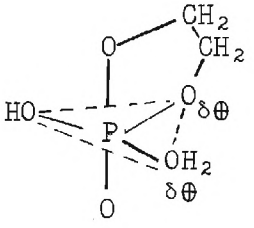
XXIIIa



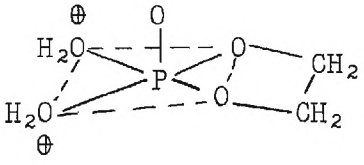
XXIIIb



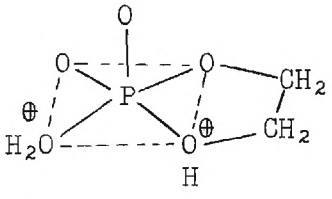
XXIVa



XXIVb



XXVa



XXVb

phosphate has been found to be 99° by X-ray diffraction studies.[43] This evidence indicates that ring strain in five-membered cyclic phosphate

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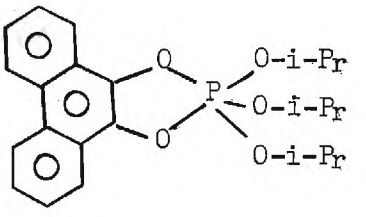
[42] W. C. Hamilton, S. J. LaPlaca, and F. Ramirez, J. Am. Chem. Soc., 87, 127 (1965).

[43] T. A. Steitz and W. N. Lipscomb, J. Am. Chem. Soc., 87, 2488 (1965).

esters arises from the constrained angle imposed on phosphorus by the five-membered ring and that relief of the strain in the transition state contributes to the rate acceleration.



XXVI

Assuming that all the 5.5 kcal/mole of strain is released in the transition state and that the relief of this strain consequently reduces the activation energy by this amount, the calculated rate factor ratio of a cyclic to a non-cyclic ester would be roughly 10^4; the total observed rate enhancement is a factor of about 10^8. Seemingly, there is at least one other factor influencing the rate of hydrolysis of the five-membered cyclic esters. A study of the P^{31} n.m.r. spectra of a number of phosphate[44,45] and phosphonate[38] derivatives has been reported. The cyclic five-membered phosphate derivatives exhibit chemical shifts which occur at a decidedly lower field than either the six-membered ring esters or acyclic phosphoryl derivatives. The five-membered ring esters thus show less electron-shielding of the phosphorus atom than acyclic and six-cyclic esters, which is consistent with the proposal that d^{π}-p^{π} bonding

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[44] R. A. Y. Jones and A. R. Katritzky, J. Chem. Soc., 4376 (1960).

[45] G. M. Blackburn, J. S. Cohen, and Lord Todd, Tetrahedron Letters, 2873 (1964).

is diminished in the five-cyclic esters. From an earlier discussion, the relative charge of a phosphorus nucleus is sensitive to changes in a substituent's ability to interact with phosphorus d orbitals. Thus, diminished ability to form d_π-p_π bonds increases the positive charge on the phosphorus, and the attraction between nucleophile and electrophile is enhanced. However, the X-ray study of Steitz and Lipscomb[43] shows that all three P-O bond lengths are equivalent in methyl ethylene phosphate, and are similar to those measured for dibenzyl phosphoric acid,[46] thus any decrease in d_π-p_π bonding is not accompanied by P-O bond lengthening.

Description of Research

Data on phosphate triesters of secondary and tertiary alcohols are very scanty. The synthesis and qualitative observations concerning the hydrolysis of tri-t-butyl phosphate have been briefly reported.[47,48] The hydrolysis of mono-t-butyl phosphate has been studied in detail by Lapidot, Samuel, and Weiss-Broday;[49] the undissociated acid undergoes facile carbon-oxygen cleavage, with formation of the t-butyl carbonium ion. Evidence has been presented that the tertiary phosphate ester of mevalonic acid pyrophosphate undergoes concerted decarboxylation and phosphate elimination to form isopropenyl pyrophosphate.[50]

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[46] J. D. Dunitz and J. S. Rollett, Acta Cryst., 9, 327 (1956).

[47] J. R. Cox, Jr. and F. H. Westheimer, J. Am. Chem. Soc., 80, 5441 (1958).

[48] V. Mark and J. R. Van Wazer, J. Org. Chem., 29, 1006 (1964).

[49] A. Lapidot, D. Samuel, J. Weiss-Broday, J. Chem. Soc., 637 (1964).

[50] K. Bloch, S. Chaykin, A. H. Phillips, and A. de Waard, J. Biol. Chem., 234, 2595 (1959).

This thesis reports a detailed study of the kinetics and mechanism of solvolysis of tri-t-butyl, tri-i-propyl, and triallyl phosphates as well as preliminary studies of the methyl pinacol phosphate system. The synthesis of t-butyl pinacol phosphate is reported and observations of its hydrolysis products recorded. Finally, the interests in the fast rates of solvolysis of five-membered ring esters of phosphoric acid have prompted the determination of the X-ray crystal structure of methyl pinacol phosphate. Detailed understanding of the bonding in these systems should locate the source of the extremely fast rates of solvolysis.

CHAPTER II

EXPERIMENTAL

Syntheses

Materials

Anhydrous pinacol (Fluka Chemical Co., purum) was dried by azeotropic distillation with benzene.[51] After the benzene was removed, calcium hydride was added to the molten pinacol and the pinacol was distilled in vacuum through a two-foot Vigreaux column.

Methanol was dried by distillation from magnesium methoxide and stored in a tightly stoppered bottle.[52a]

Diethyl ether was dried over and distilled from lithium aluminum hydride immediately before use. Pentane, when used as a solvent in the chloridite preparation, was dried and stored over sodium metal wire.

Pyridine was boiled under reflux with calcium hydride, distilled, and stored over potassium hydroxide.[52b]

Triethylamine was dried by boiling under reflux with and distillation from BaO[52b] and then subjected to careful distillation through a three-foot vacuum-jacketed column filled with glass helices. Cyclohexylamine was boiled under reflux with BaO and distilled.

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51 E. C. Horning, Org. Syntheses, Coll. Vol. III, p. 313.

52 (a) K. B. Wiberg, "Laboratory Technique in Organic Chemistry," McGraw-Hill Book Co., Inc., New York, N. Y. (1960), p. 242; (b) ibid., pp. 247-8.

Phosphorus trichloride was freshly distilled before its use in a reaction.

Dinitrogen tetroxide was synthesized by reaction of nitric oxide and oxygen.[53] An evacuated gas manifold and an attached 12-liter flask was filled with nitric oxide to slightly less than one atmosphere pressure. Oxygen was introduced to the system through another port in the manifold system. Oxygen was added until the pressure no longer decreased following its addition. One neck of a collection flask was attached to a port of the manifold system and another neck of the flask connected to a vacuum pump. The body of the flask was immersed in liquid nitrogen. The vacuum pump was started and the dinitrogen tetroxide collected and stored in the collection flask.

Other reagents were used without special purification. The n.m.r. spectrum of triallyl phosphate used in the kinetic studies is shown in Fig. 8.

Tri-t-butyl Phosphite[47,48]

Fifteen hundred milliliters of petroleum ether (b.p. 30-60°C) were placed in a five-liter three-necked flask which was equipped with a dropping funnel, a mechanical stirrer, and a thermometer dipping below the surface of the petroleum ether. Triethylamine (315 g., 3.12 moles) and t-butyl alcohol (225 g., 3.04 moles) were then added to the flask. Stirring was begun and the flask and contents were cooled to below 0° (-10 to 0°C) in an ice-salt mixture. Phosphorus trichloride (123 g., 0.895 moles) dissolved in 1000 ml. of petroleum ether was added dropwise to the

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[53] We thank Dr. James D. Ray for suggesting this procedure for the preparation of dinitrogen tetroxide.

cold mixture over a period of about six hours. During the addition of phosphorus trichloride the temperature was maintained between -10° and 0°C. After addition of phosphorus trichloride was complete, 1500 ml. of water were added to dissolve the precipitated amine hydrochloride. The aqueous layer was separated from the organic layer in a six-liter separatory funnel. The organic phase, containing tri-t-butyl phosphite, was washed twice with approximately 500 ml. of saturated sodium bicarbonate, then with about 500 ml. of water. The organic layer was dried with anhydrous calcium chloride and the petroleum ether solution was evaporated on a rotary evaporator under aspirator vacuum. After evaporation of the petroleum ether about 220 g. of crude tri-t-butyl phosphite was obtained.

The crude tri-t-butyl phosphite was distilled at 3 mm pressure, yielding approximately 160 g. (71% of theory) of a liquid which boiled at 67-69°C. Upon storage in a refrigerator, the liquid solidified (m.p. approximately 10°C). An infrared spectrum (Fig. 2) of the material indicated no P-H stretch in the 4.5 μ region and the n.m.r. spectrum (Fig. 3) showed a single, clean peak at 1.34 p.p.m. downfield from tetramethylsilane (neat liquid). Subsequent conversion of this material into tri-t-butyl phosphate by oxidation demonstrated its purity. Traces of acidic impurities might account for the reported instability of tri-t-butyl phosphite to distillation.[48]

Tri-t-butyl Phosphate[47]

Tri-t-butyl phosphite (50 g., 0.20 mole) dissolved in 100 ml. of petroleum ether (b.p. 30-60°C) in a 300-ml. Erlenmeyer flask was cooled in an ice bath. Dinitrogen tetroxide was passed into the cold mixture,

which was stirred on a magnetic stirrer. Addition of dinitrogen tetroxide was continued until the solution developed a green color (probably N_2O_3) or until unreacted NO_2 escaped from the reaction mixtures. The solution was washed with 100 ml. of saturated sodium bicarbonate solution, then with water, and was dried over anhydrous calcium chloride. The dried solution was cooled in a dry ice-acetone bath, whereupon the tri-t-butyl phosphate (35 g., m.p. 67-70°) crystallized and was separated on a Buchner funnel. A second crop could be obtained by concentrating the mother liquid under vacuum, and cooling. Recrystallization was effected by dissolving in petroleum ether at room temperature and cooling in dry ice-acetone. The melting point after two such recrystallizations was 73-73.5°C. The IR and n.m.r. spectra of this material are shown in Figs. 4 and 5, respectively.

Cyclohexylammonium Di-t-butyl Phosphate

Cyclohexylamine (0.8156 g., 8.24 mmole) was placed in a 50-ml. volumetric flask and diluted to 50 ml. with 50% v/v water-ethanol solution. The contents were transferred to a polyethylene bottle and thermostated at 60°C. Tri-t-butyl phosphate (2.0069 g., 7.53 mmole) was then added to the solution. After two days, when the reaction was complete, the contents of the bottle were emptied into a 100-ml. round-bottomed flask and the solvent distilled under aspirator vacuum. The solid remaining in the flask was dried under vacuum. The cyclohexylammonium di-t-butyl phosphate (2.287 g., 98% of theory) recrystallized from boiling 1,2-dimethoxyethane (about 0.5 g. salt/25 ml. of DME) in needles, m.p. after three recrystallizations 189.8-190.8°, decomp.

Anal. $C_{14}H_{32}PO_4N$ Calc'd: C, 54.35; H, 10.43; N, 4.53; P, 10.01

Found : C, 53.96; H, 10.34; N, 4.48, P, 10.00

The n.m.r. spectrum of this salt in D_2O is recorded in Fig. 22.

Tri-i-propyl Phosphate

Tri-i-propyl phosphite (Matheson, Coleman and Bell) was oxidized with dinitrogen tetroxide[47] while being cooled in an ice bath. The product, which distilled at 71-72°C at 1 mm pressure, was a colorless liquid. The n.m.r. spectra of both the phosphite and phosphate are shown in Figs. 6 and 7, respectively.

Pinacol Phosphorochloridite

The method of Arbuzov and Azanovskaya[54] was followed with slight modification. Pentane as solvent in this reaction gave essentially the same results as diethyl ether and was more easily dried. Typically, pinacol (59.0 g., 0.50 mole) and pyridine (79.1 g., 1.00 mole) were dissolved in 400 ml. of dry ether (or pentane) in a dry one-liter three-necked flask equipped with a mechanical stirrer, a dropping funnel, and a thermometer dipping below the surface of the solution. The flask was placed in an ice-salt bath, stirring was begun, and the contents cooled below 0°C. Phosphorus trichloride (69 g., 0.5 mole) was added dropwise to the cold mixture at a rate such that the temperature would be maintained below 0°C. Addition required about six hours. After addition was completed, the mixture was boiled under reflux for 30 minutes. When the reaction mixture had cooled to room temperature, pyridine hydrochloride was removed by vacuum filtration. Usually, after filtering the pyridine

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[54] A. E. Arbuzov and M. M. Azanovskaya, Izv. Akad. Nauk SSSR, Otd. Khim Nauk, 473 (1949).

hydrochloride, the filtrate was cloudy or contained a precipitate which was probably due to formation of the hydrolysis product of the chloridite. Further filtrations only needlessly exposed the active chloridite to more atmospheric moisture. The solvent was removed by distillation or by use of a rotary evaporator. A yellow, fuming liquid (70-75 g.) was obtained, which upon cooling in the refrigerator precipitated more pinacol phosphate. Filtering the phosphonate and distilling the filtrate under vacuum (b.p. 53°/3 mm) yielded a colorless, fuming liquid. Yields of pure chloridite were low, usually in the range of 25% of theory (20-25 g.). A large amount of an orange, nonvolatile, tarry residue remained in the distilling flask. An n.m.r. spectrum of pinacol phosphrochloridite is recorded in Fig. 9.

Pinacol phosphonate[54] which accompanied this reaction could be purified by sublimation at steam bath temperatures at 0.1-0.2 mm. pressure (m.p. 103-105°C). The IR and n.m.r. spectra are shown in Figs. 10 and 11, respectively.

Methyl Pinacol Phosphite[54]

Pinacol phosphorochloridite (20.0 g., 0.11 mole) was dissolved in 30 ml. of petroleum ether (b.p. 30-60°C) in a 100-ml. Erlenmeyer flask stoppered with a serum cap. A solution of dry methanol (3.60 g., 0.112 mole) and triethylamine (12.00 g., 0.119 mole) was injected into the solution through the serum cap with a hypodermic syringe. During the addition, the solution was cooled in an ice bath and stirring maintained with a mechanical stirrer. After addition was completed, the triethylamine hydrochloride was filtered, the solvent removed on a rotary evaporator, and the concentrate distilled under vacuum, (b.p. 25-28°C/1 mm). In this

manner, 9-10 g. of methyl pinacol phosphite was obtained (50% of theory).

Alternatively, for larger preparations, the reaction was performed in a three-necked, round-bottomed flask, adding the triethylamine-methanol mixture to the chloridite through a dropping funnel, while stirring with a mechanical stirrer and cooling in ice. Yields with this procedure were similar. Figs. 12 and 13 show the recorded IR and n.m.r. spectra, respectively.

Methyl pinacol phosphite was extremely reactive toward water, producing pinacol phosphonate. Added to a small test tube containing water, it dissolved instantly with the liberation of heat. Care was required in the above reactions and in further handling of both the chloridite and phosphite to avoid exposure to moisture.

Methyl Pinacol Phosphate

Methyl pinacol phosphite (10.0 g., 0.056 mole) was dissolved in 50 ml. of petroleum ether in a 100-ml. flask. Dinitrogen tetroxide vapors were passed into the mixture,[47] while the flask and contents were cooled in an ice bath. The mixture was stirred with a magnetic stirrer. Methyl pinacol phosphate soon precipitated from the mixture. The end of the reaction was indicated by the escaping of red vapors of NO_2 from the flask or by formation of a green color in the solution. The ether was removed, leaving a slightly yellow solid. Generally, 9.5-10.5 g. of solid were obtained (95% of theory).

Purification of methyl pinacol phosphate could be effected by recrystallizations from benzene or petroleum ether (b.p. 90-120°C) but a severe loss of material accompanied these methods. Purification by sublimation at steam bath temperatures at 0.1-0.2 mm proved to be the best

method. After one sublimation, the melting point was 99.8-100.8°C. The IR and n.m.r. spectra are recorded in Figs. 14 and 15, respectively.

Anal. $C_7H_{15}PO_4$ Calc'd: C, 43.30; H, 7.79; P, 15.95

Found : C, 43.32; H, 8.05; P, 15.98

Methyl pinacol phosphate also could be prepared from pinacol phosphonate. Pinacol phosphonate (5.89 g., 35.9 mmole) was dissolved in 25 ml. of chloroform in a 50-ml. flask. N-chlorosuccinimide (4.80 g., 36.0 mmole) was added in small portions while the flask was cooled in ice.[55] After all the N-chlorosuccinimide had been added, the solution was boiled under reflux on the steam bath for 30 minutes. The solution was cooled and a mixture of methanol (1.2 g., 37.5 mmole) and triethylamine (4.0 g., 39.6 mmole) was added in small portions. Upon completion of the addition of methanol and triethylamine, the amine hydrochloride and succinimide were removed by filtration. The filtrate was concentrated on a rotary evaporator and a brown, oily mass resulted. This material was washed with water and two phases resulted. The organic layer, dark brown in color, contained mostly chloroform. Evaporation of the chloroform in a watch glass by a stream of air left a dark brown solid. This solid was washed with petroleum ether, which removed much of the brown color but dissolved very little of the solid. The solid melted at 95-100°C and gave n.m.r. and IR spectra identical with those of methyl pinacol phosphate. After one sublimation, 2.04 g. of purified methyl pinacol phosphate were obtained, m.p. 99.2-101°C.

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[55] This procedure is a modification of the one described by G. W. Kenner, A. R. Todd, and F. J. Weymouth, J. Chem. Soc., 3675 (1952).

t-Butyl Pinacol Phosphite

Pinacol phosphorochloridite was treated with an equivalent each of t-butyl alcohol and triethylamine in petroleum ether as in the preparation of methyl pinacol phosphite. After the amine hydrochloride was filtered and the filtrate concentrated on a rotary evaporator, the concentrate was distilled under vacuum. The n.m.r. and IR spectra (Figs. 16 and 17, respectively) agree with the formulation of the compound as t-butyl pinacol phosphite.

Preparation of t-Butyl Pinacol Phosphate

Oxidation of t-butyl pinacol phosphite with dinitrogen tetroxide[47] in petroleum ether yielded a white solid, which was formulated as t-butyl pinacol phosphate on the basis of its IR and n.m.r. spectra (Figs. 18 and 19, respectively). The melting point after two sublimations at approximately 60-70°C at 0.1 mm pressure was 70.4-71.8°C.

Anal. $C_{10}H_{21}PO_4$ Calc'd: C, 50.80; H, 8.9 ; P, 13.15

Found : C, 50.60; H, 8.90; P, 13.25

Samples of t-butyl pinacol phosphite and t-butyl pinacol phosphate were prepared by Mr. Kary Mullis.

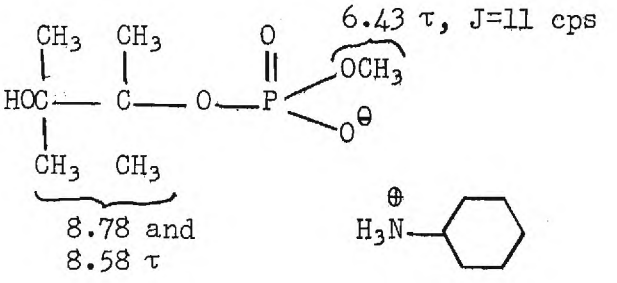
Hydrolysis of Methyl Pinacol Phosphate

Basic Solution. An attempt to follow the kinetics of the basic hydrolysis of methyl pinacol phosphate revealed the extremely labile nature of this compound in basic solution. Fifty milliliters of 0.08 N NaOH solution in 50% 1,2-dimethoxyethane-water was made 0.5 in ionic strength with $NaClO_4$ and the solution equilibrated at 30°C. Three millimoles, 0.5831 g., of methyl pinacol phosphate were added and a 4.00-ml. aliquot withdrawn and titrated with 0.0495 N hydrochloric acid to pH 7.

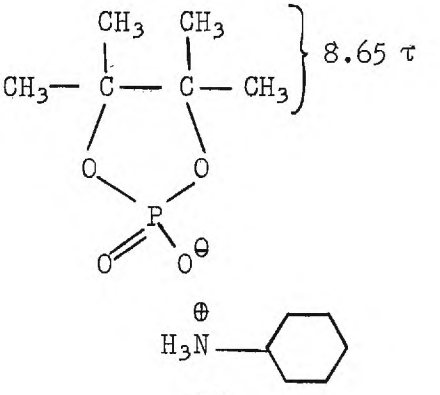
The sample required 0.80 ml. of the hydrochloric acid solution whereas a 4.00-ml. aliquot of the NaOH solution without added phosphate required 5.63 ml. of the same acid. The hydrolysis of the phosphate was essentially complete in about 60 seconds, the time required to mix the solution, withdraw the aliquot, and titrate the sample.

To investigate the products of basic hydrolysis of methyl pinacol phosphate, 3.00 g., 0.0154 mole, of the ester were dissolved in 100 ml. of 50% 1,2-dimethoxyethane-water solution to which 2.00 ml., 0.0165 mole, of cyclohexylamine was added. After a few hours reaction time, the solvent and remaining cyclohexylamine were removed by vacuum distillation. A brown solid, 3.81 g., was obtained. After one recrystallization from 1,2-dimethoxyethane, the n.m.r. spectrum of the reaction product in D_2O was obtained (Fig. 25). Two peaks at 8.78 and 8.58 τ were attributed to the two different types of methyl groups in the ring-opened salt (I). A doublet, centered at 6.43 τ, J = 11 cps, indicated a methyl group attached to a phosphate residue. A small peak at 8.65 τ was attributed to ring-retained salt (II). Integration of the spectrum was obscured in the methyl region by the broad peak from 7.8-9.0 τ due to the cyclohexylammonium cation protons. However, there was approximately 80% ring-opened salt (I) and 20% ring-retained salt (II). Repeated recrystallizations of the salt from 1,2-dimethoxyethane gave little separation of either reaction product, as indicated by NMR. The IR of this material is shown in Fig. 24.

Neutral Solution. Methyl pinacol phosphate (3.00 g., 0.0154 mole) was dissolved in 100 ml. of 50% 1,2-dimethoxyethane-water and after a few hours of reaction, the solvent was removed by vacuum distillation.



I



II

A white solid, 1.71 g., m.p. 191°, decomp., was obtained. An n.m.r. spectrum of this material (Fig. 21) showed two peaks, $\tau = 8.66$ (relative area = 12) and $\tau = -0.54$ (relative area = 1). The material, therefore, formulated as pinacol phosphoric acid. The IR spectrum agrees with this formulation (Fig. 20).

Anal. $C_6H_{13}PO_4$ Calc'd: C, 40.00; H, 7.27; P, 17.19

Found : C, 39.44; H, 7.26; P, 17.34

This is the only observed product of hydrolysis in initially neutral 1,2-dimethoxyethane-water solution.

Treating the acid with an equivalent of cyclohexylamine in 1,2-dimethoxyethane produced the cyclohexylammonium salt which precipitated quantitatively. The single, sharp n.m.r. peak of the salt in D_2O, other than those of cyclohexylammonium ion, was positioned at $\tau = 8.64$ (Fig. 23).

Hydrolysis of t-Butyl Pinacol Phosphate

Basic Solution. Cyclohexylamine, 1.7 ml., 0.014 mole, was dissolved in a solution of 50 ml. of 1,2-dimethoxyethane and 50 ml. of water. t-Butyl pinacol phosphate (3.00 g., 0.0127 mole) was added and allowed to react overnight. The solvent was removed by vacuum distillation, leaving

3.27 g. of a white solid. An n.m.r. spectrum in D_2O revealed a single methyl peak at 8.64 τ, indicating that the only product of hydrolysis is the ring-retained salt (Fig. 23).

Neutral Solution. t-Butyl pinacol phosphate, 3.00 g., 0.0127 mole, was dissolved in a solution of 50 ml. of 1,2-dimethoxyethane and 50 ml. of water. The reaction was allowed to proceed overnight. The solvent was removed by vacuum distillation. The solid obtained, 1.49 g., proved to be identical in melting point, 141°, IR, and NMR spectra with pinacol phosphoric acid obtained from neutral hydrolysis of methyl pinacol phosphate.

Further proof of the identity of the reaction product was provided by the conversion of it to methyl pinacol phosphate. Pinacol phosphoric acid, 1.605 g., 0.0892 mole, was placed in a 125-ml. Erlenmeyer flask and covered with 50 ml. of diethyl ether. The solution was stirred on a magnetic stirrer. Small portions of diazomethane in ether solution were added to the acid until the pale yellow color of diazomethane persisted. During addition of diazomethane, vigorous gas evolution occurred and the solution remained colorless until excess diazomethane was added. The ether was removed on a rotary evaporator, whereupon a slightly discolored solid remained. Sublimation of the solid at steam bath temperatures at 1 mm pressure gave 1.26 g. (6.49 mmole, 73% of theory) of methyl pinacol phosphate, m.p. 99.8-101.0°C. No depression of melting point occurred when it was mixed with a sample of the ester prepared by oxidation of methyl pinacol phosphite.

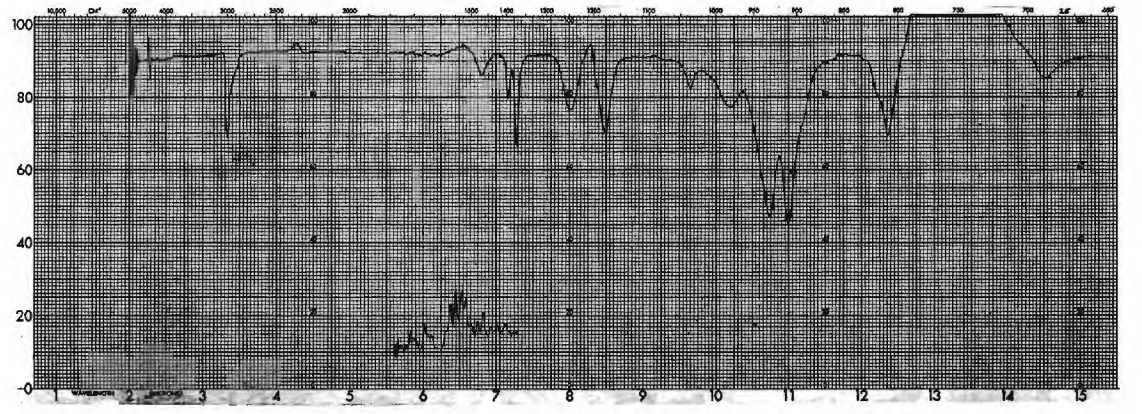


Fig. 2. IR spectrum of tri-t-butyl phosphite ($CHCl_3$ solution, 0.1 mm matched cells).

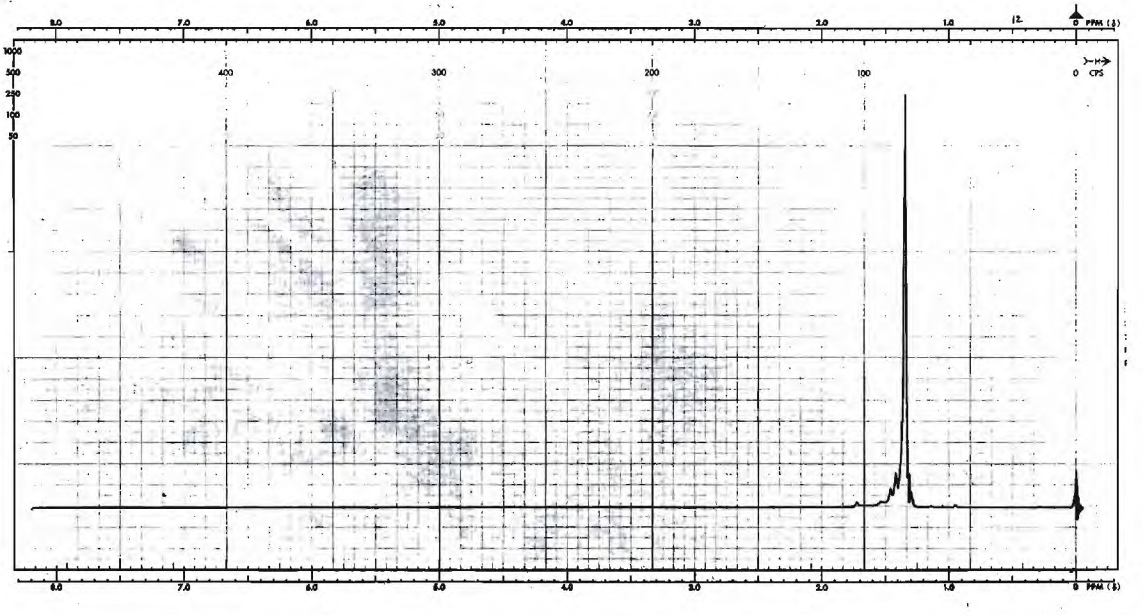


Fig. 3. 500 cps NMR spectrum of tri-t-butyl phosphite (neat liquid).

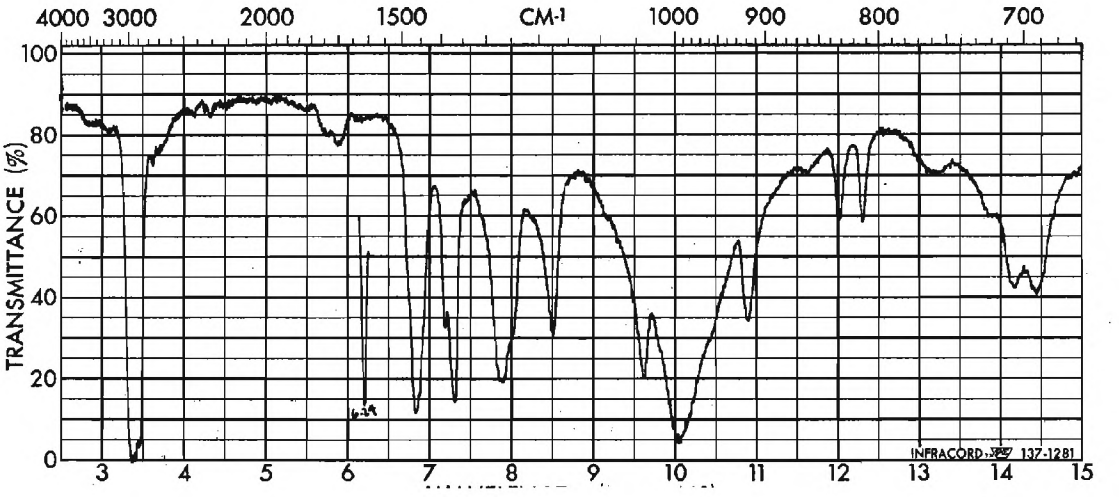


Fig. 4. IR spectrum of tri-t-butyl phosphate (nujol mull).

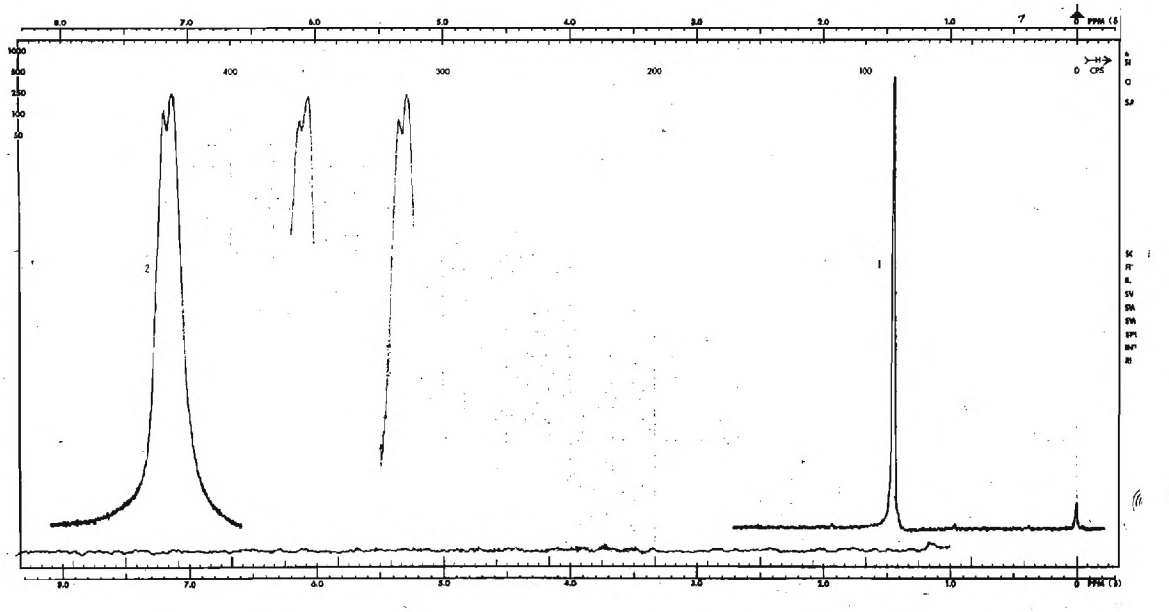


Fig. 5. (1) 500 cps NMR spectrum of tri-t-butyl phosphate (CCl_4 sol'n); (2) 50 cps NMR spectrum of the 8.57 τ peak showing splitting of 0.5 cps.

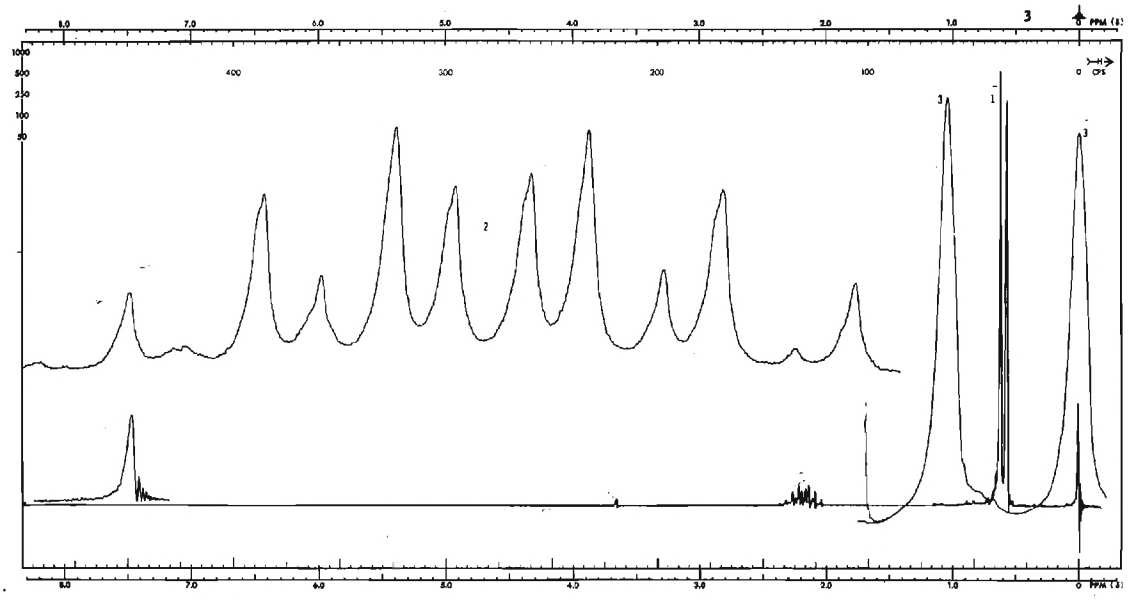


Fig. 6. (1) 500 cps NMR spectrum of tri-i-propyl phosphite (neat liquid); (2) 50 cps NMR spectrum of peaks centered at 7.82 τ; (3) 50 cps NMR spectrum of peaks centered at 9.40 τ.

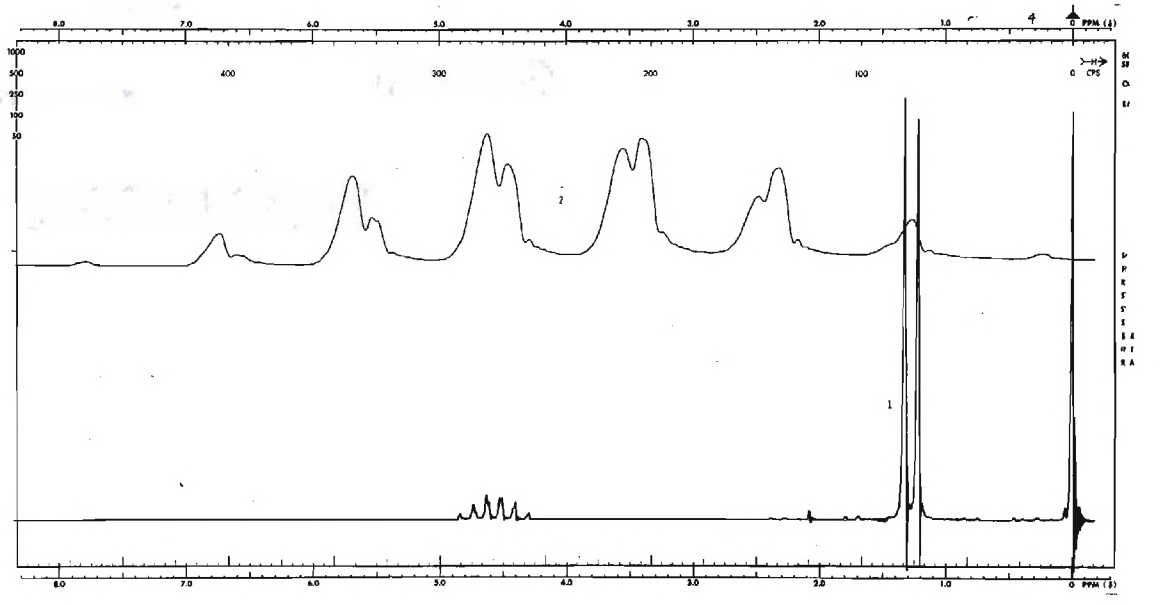


Fig. 7. (1) 500 cps NMR spectrum of tri-i-propyl phosphate (neat liquid); (2) 50 cps NMR spectrum of the peaks centered at 5.44 τ.

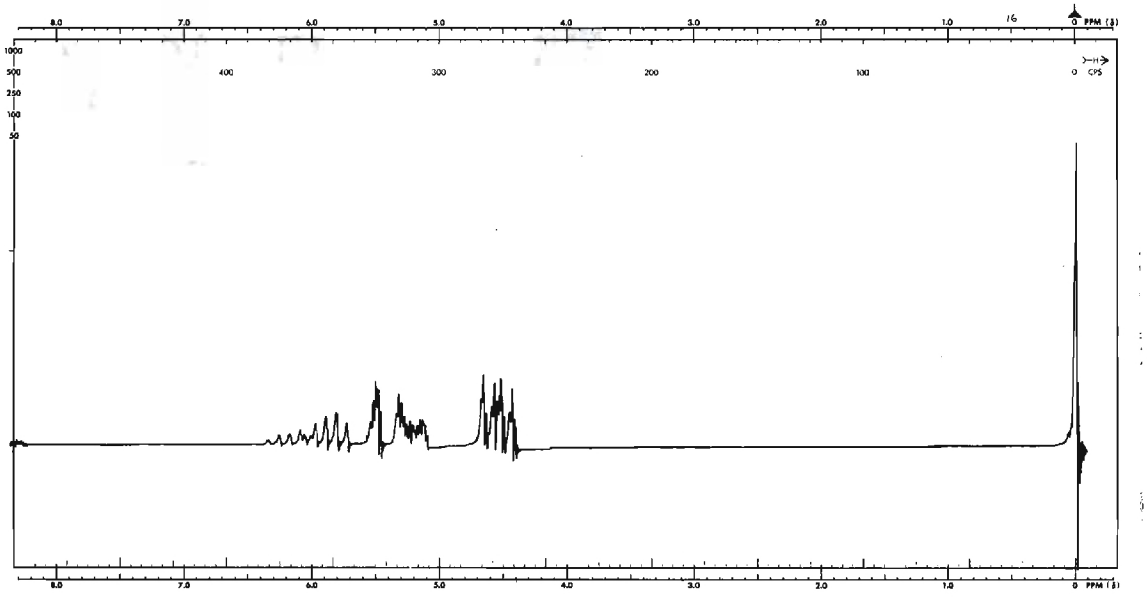


Fig. 8. 500 cps NMR spectrum of triallyl phosphate (neat liquid).

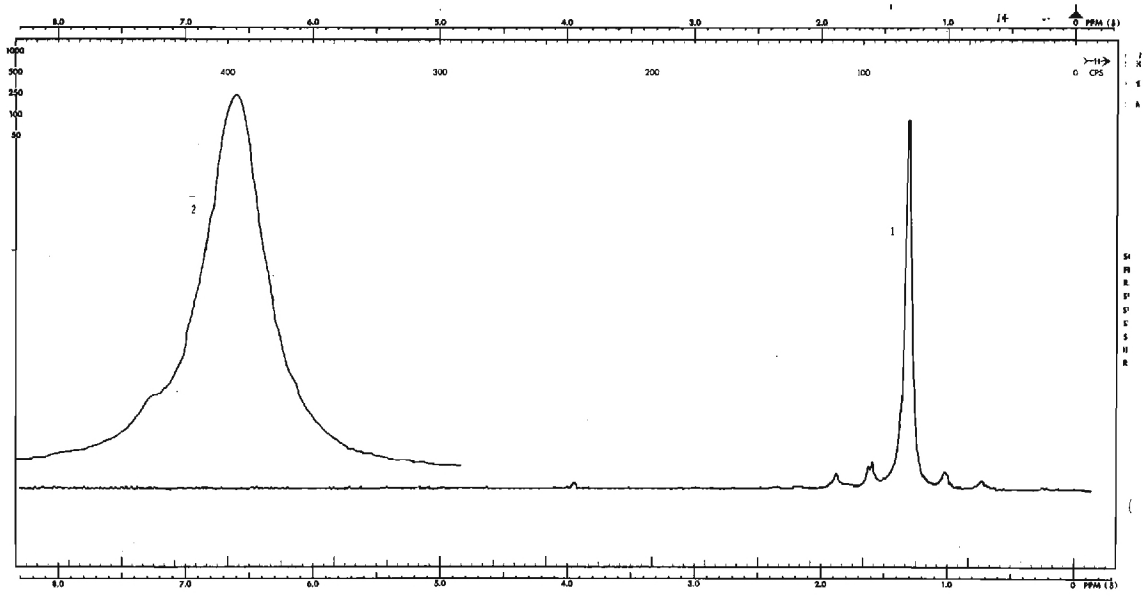


Fig. 9. (1) 500 cps NMR spectrum of pinacol phosphorochloridite (neat liquid); (2) 50 cps spectrum of the peak at 8.70 τ.

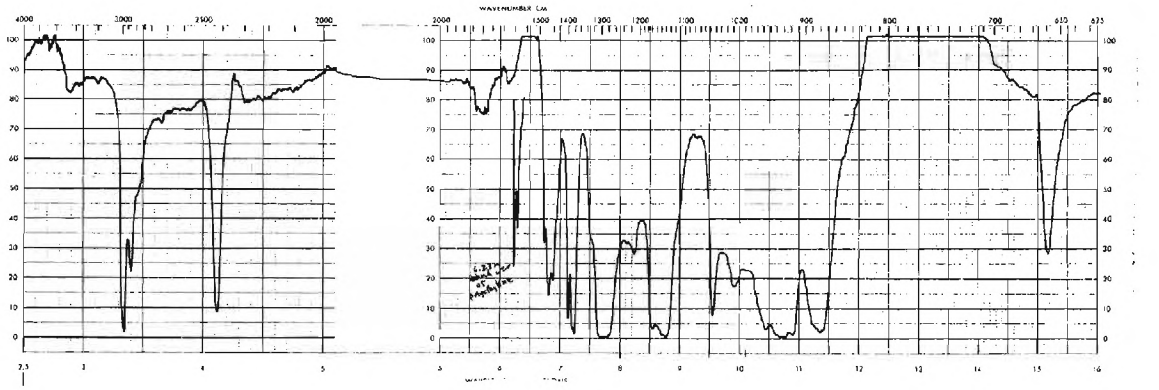


Fig. 10. IR spectrum of pinacol hydrogenphosphonate (CCl_4 sol'n, 0.5 mm matched cells).

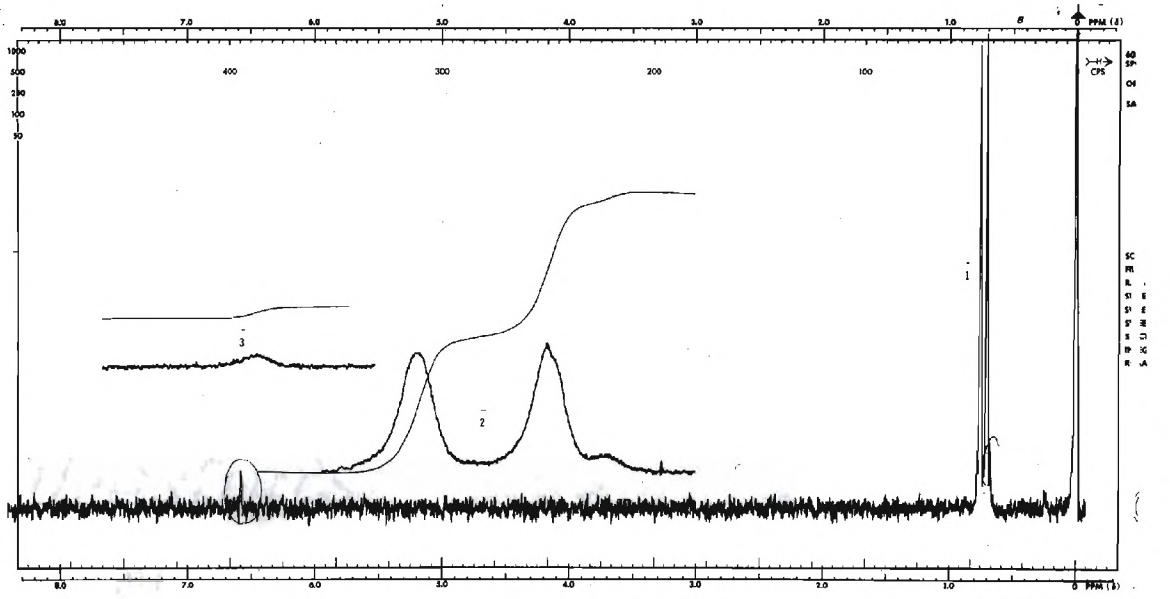


Fig. 11. (1) 1000 cps NMR spectrum of pinacol hydrogenphosphonate ($CDCl_3$ sol'n); (2) 50 cps NMR spectrum of the 8.4 to 8.8 τ region; (3) 50 cps spectrum of the peak at -3.16 τ.

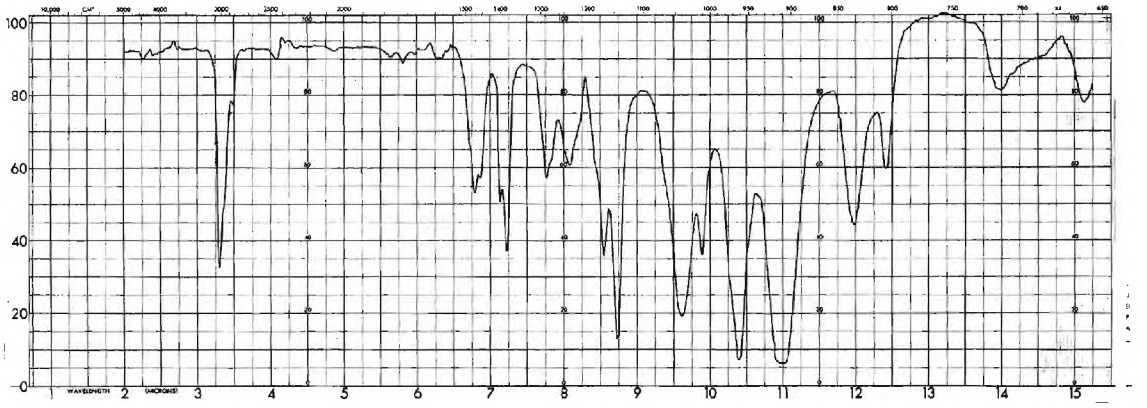


Fig. 12. IR spectrum of methyl pinacol phosphite ($CHCl_3$ sol'n, 0.1 mm matched cells).

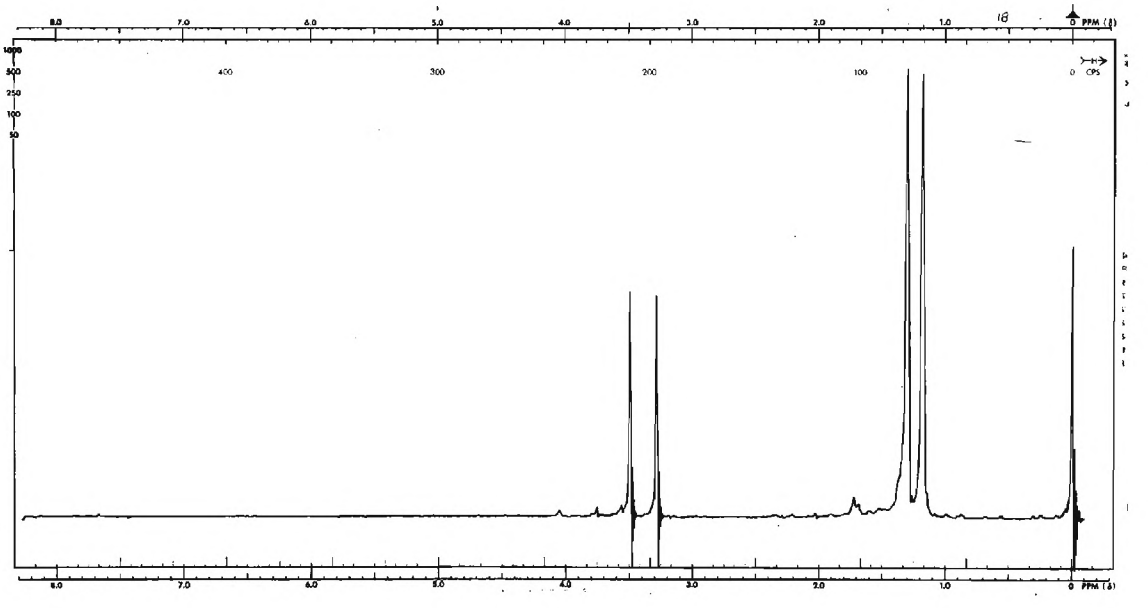


Fig. 13. 500 cps NMR spectrum of methyl pinacol phosphite (neat liquid).

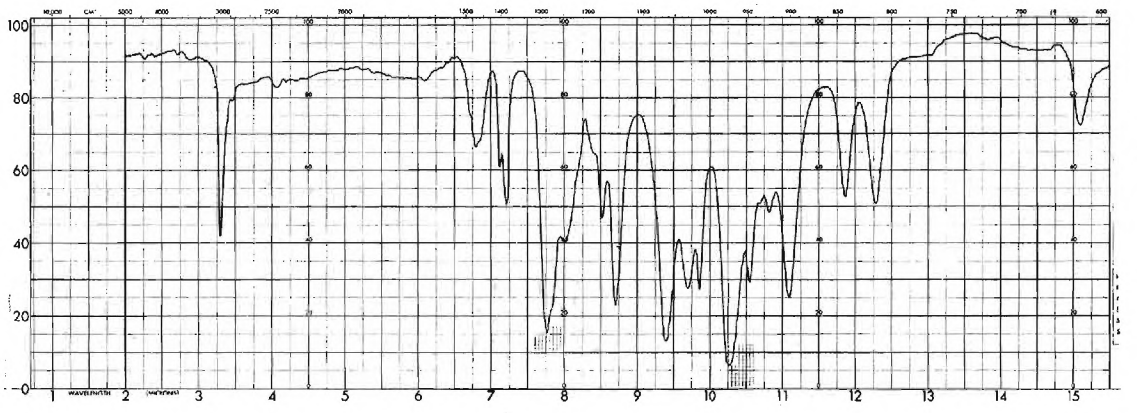


Fig. 14. IR spectrum of methyl pinacol phosphate ($CHCl_3$ solution, 0.1 mm matched cells).

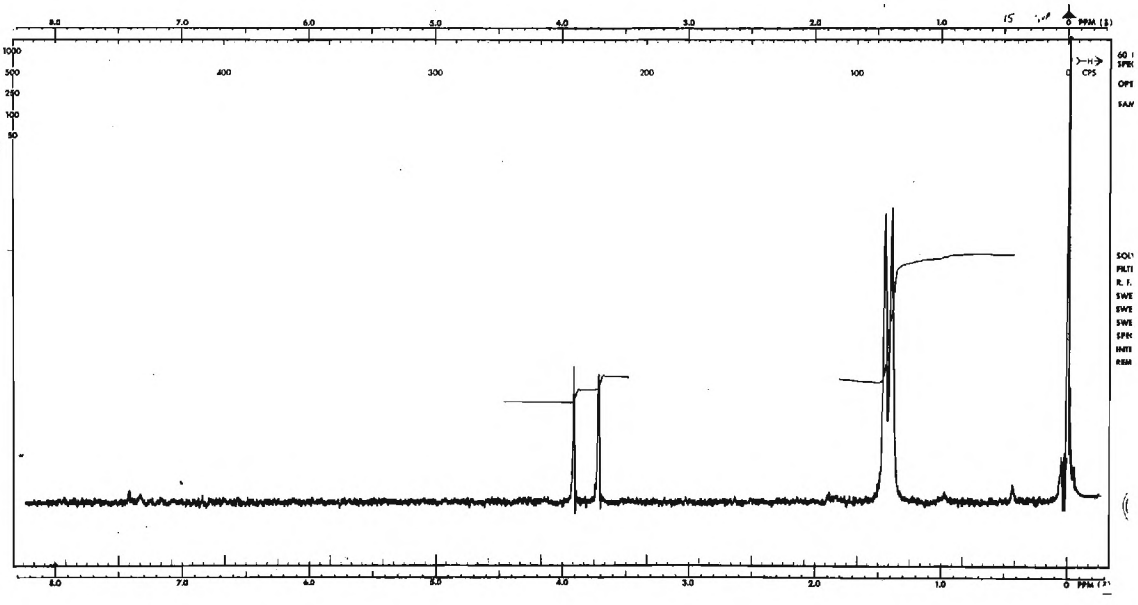


Fig. 15. 500 cps NMR spectrum of methyl pinacol phosphate ($CDCl_3$ solution).

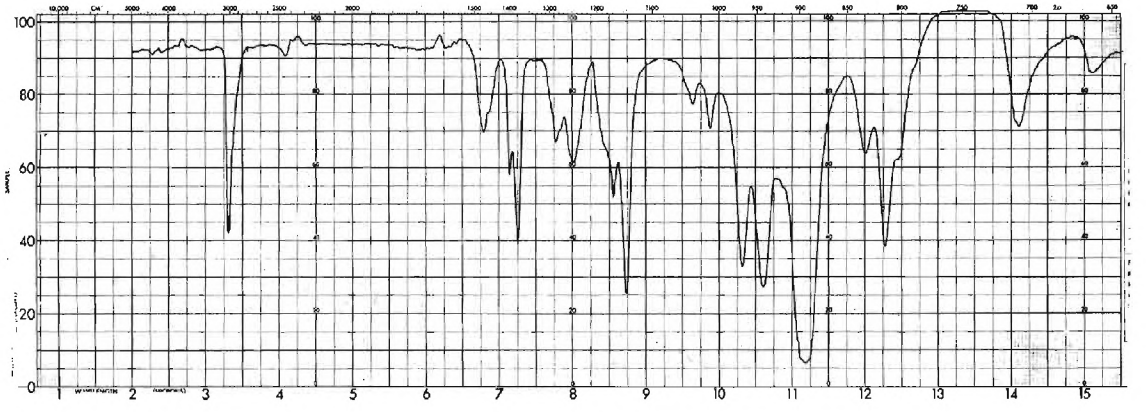


Fig. 16. IR spectrum of t-butyl pinacol phosphite ($CHCl_3$ solution).

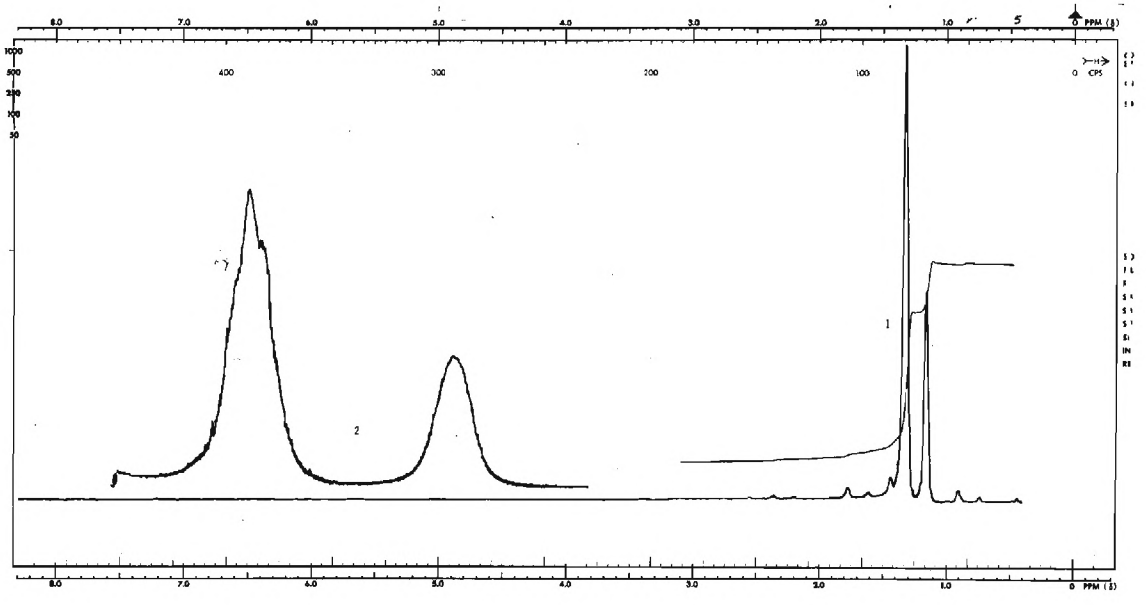


Fig. 17. The NMR spectrum of t-butyl pinacol phosphite (neat liquid). (1) 500 cps sweep width; (2) 50 cps sweep width of the region from 8.6 to 8.9 τ.

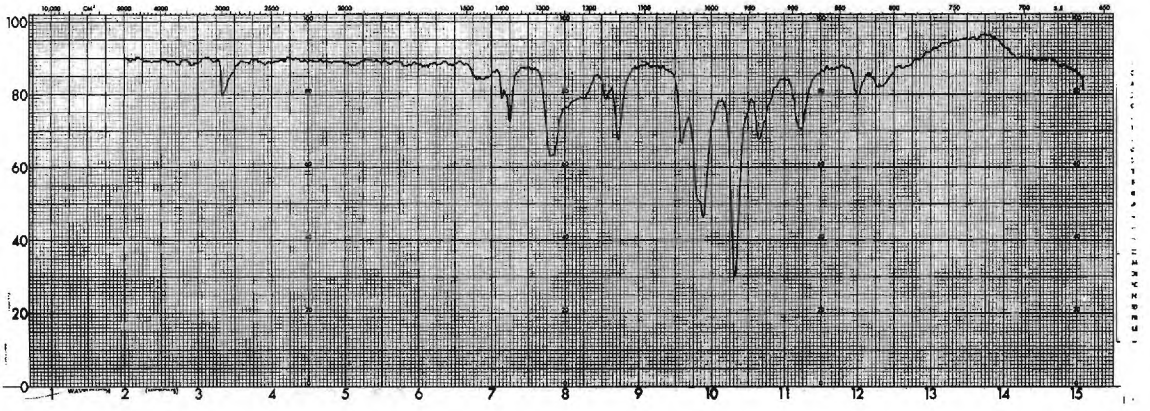


Fig. 18. IR spectrum of t-butyl pinacol phosphate ($CHCl_3$ solution, 0.1 mm matched cells).

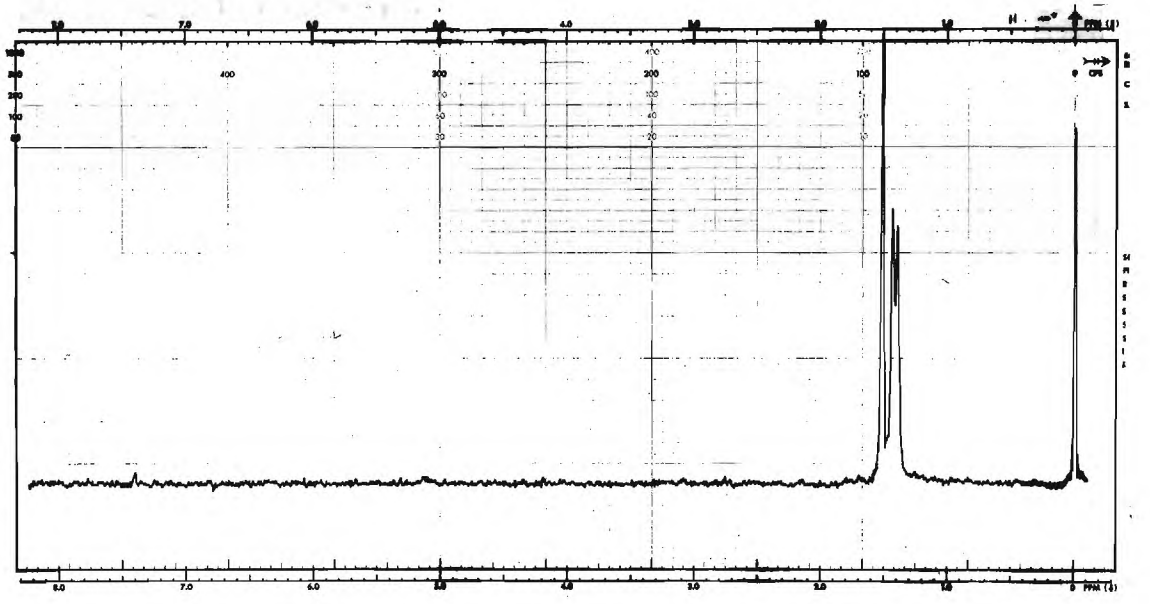


Fig. 19. NMR spectrum of t-butyl pinacol phosphate in $CDCl_3$ (500 cps sweep width).

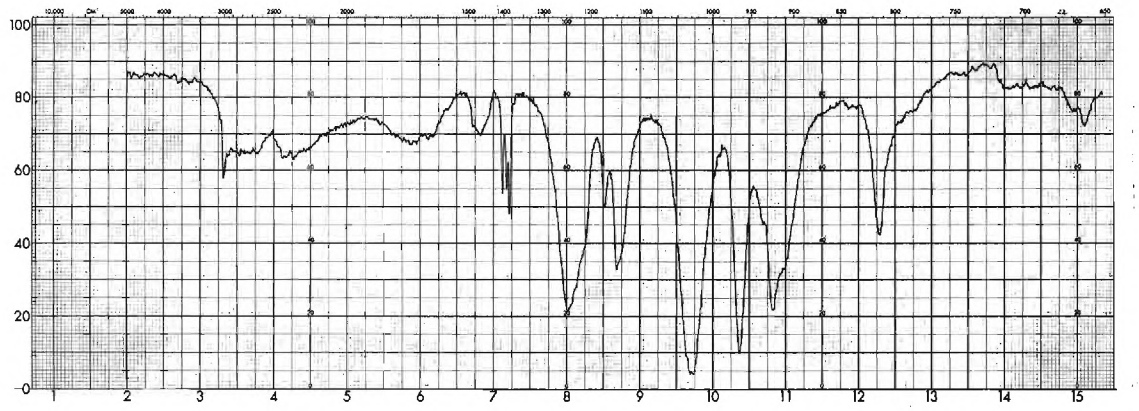


Fig. 20. IR spectrum of pinacol phosphoric acid ($CHCl_3$ solution, 0.1 mm matched cells).

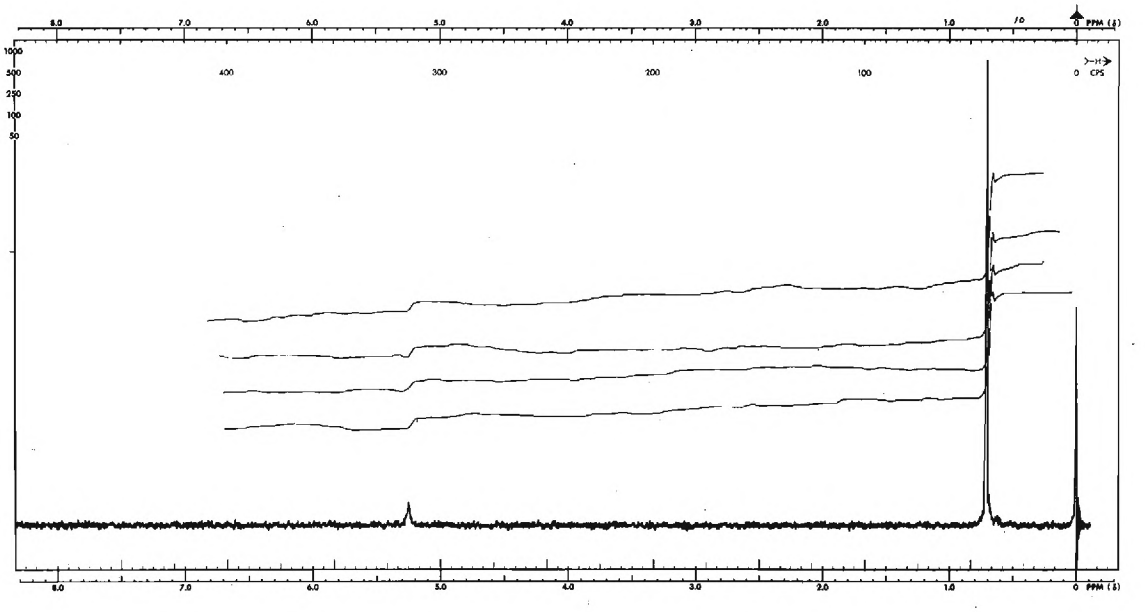


Fig. 21. NMR spectrum of pinacol phosphoric acid ($CDCl_3$ solution, 1000 cps sweep width).

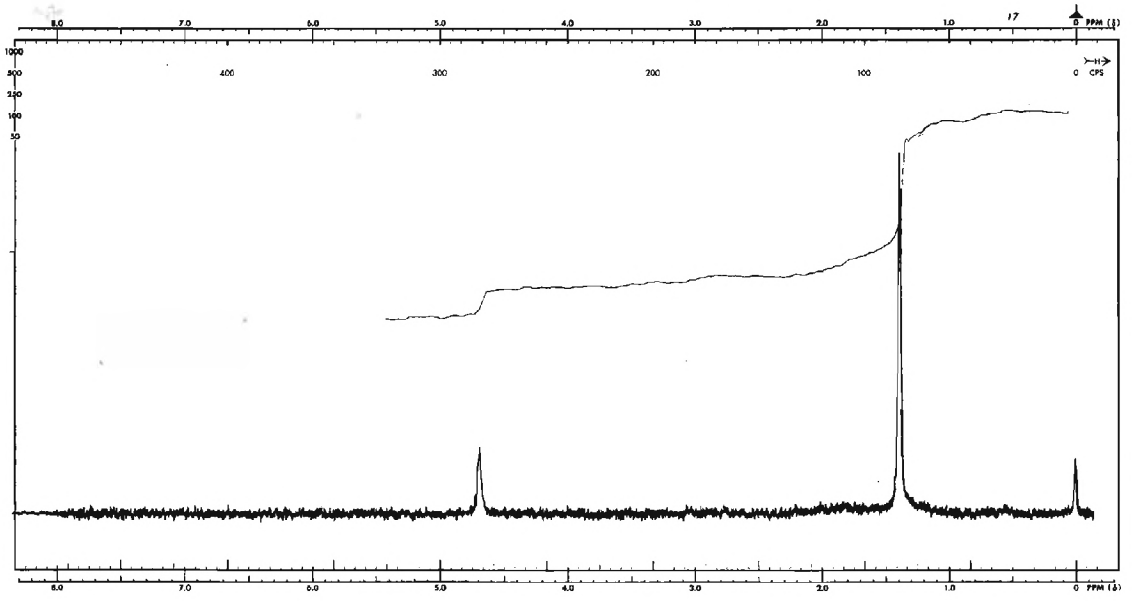


Fig. 22. NMR spectrum of cyclohexylammonium di-t-butyl phosphate (D_2O solution, 500 cps sweep width).

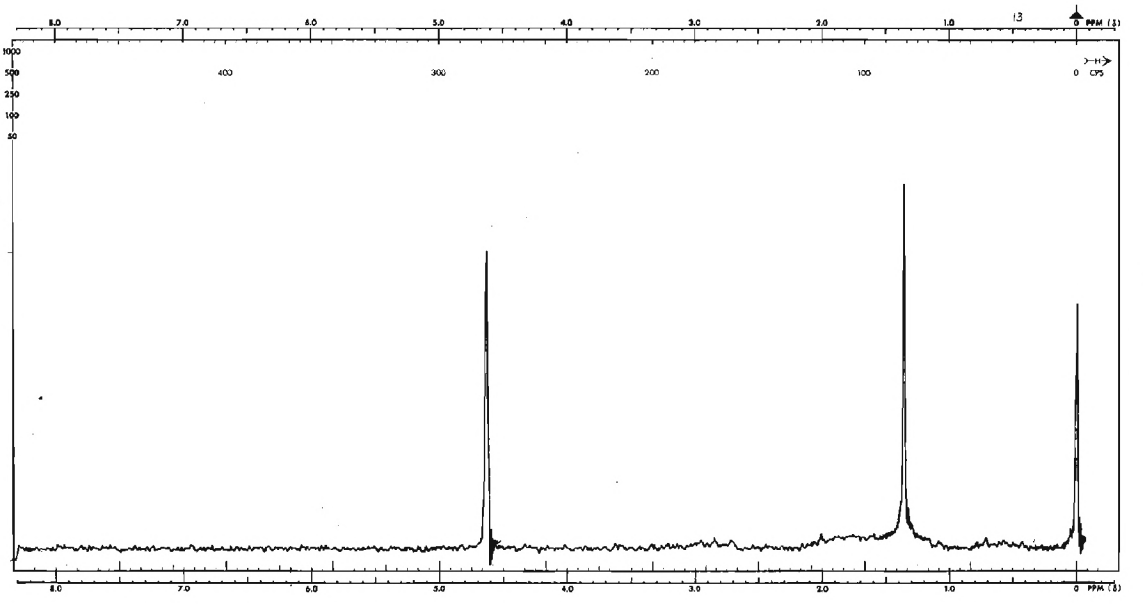


Fig. 23. NMR spectrum of cyclohexylammonium pinacol phosphate (D_2O solution, 500 cps sweep width).

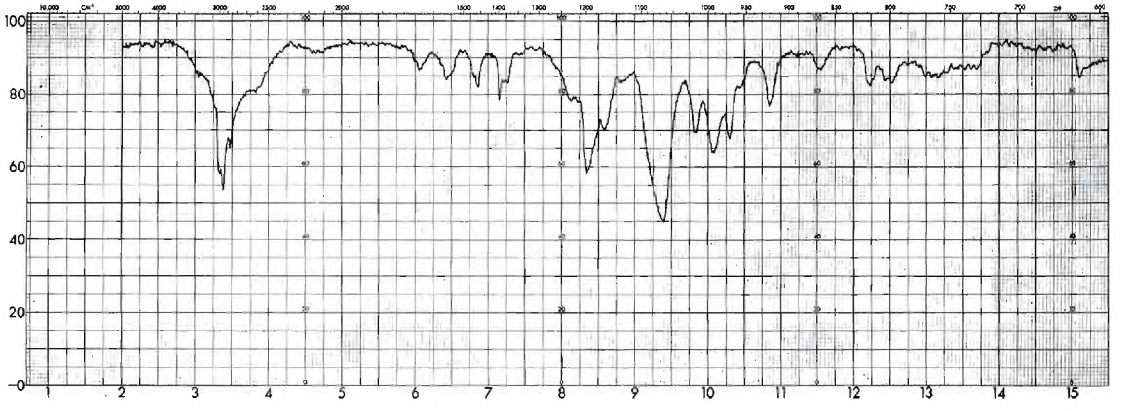


Fig. 24. IR spectrum of cyclohexylammonium methyl 3-hydroxy-2,3-dimethyl butyl-2-phosphate ($CHCl_3$ solution, 0.1 mm matched cells) contaminated with cyclohexylammonium pinacol phosphate (see text).

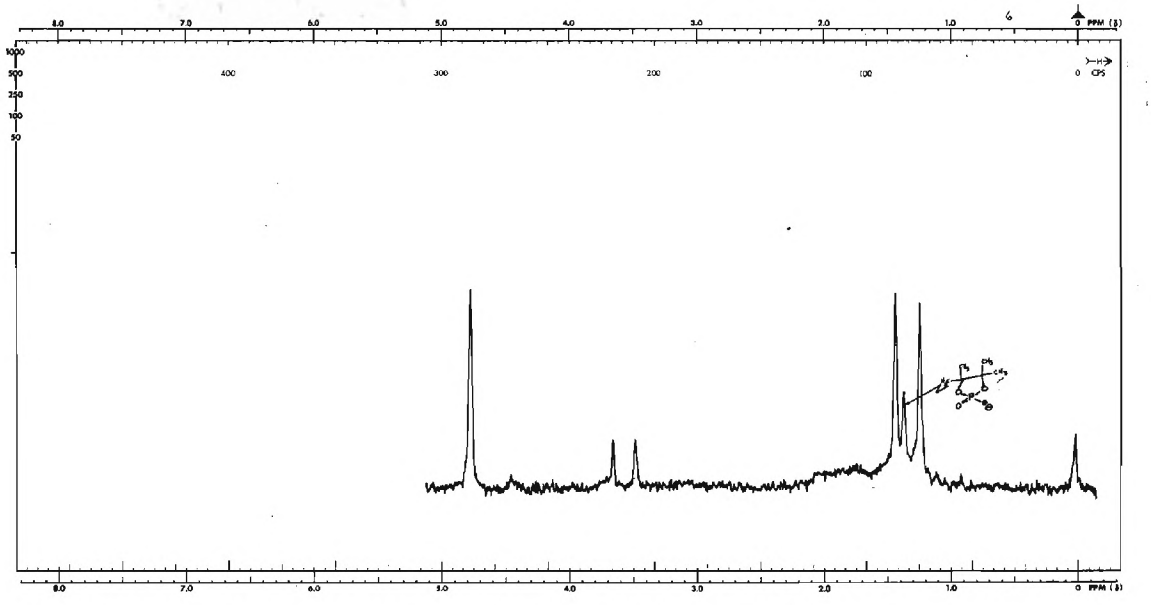


Fig. 25. NMR spectrum of cyclohexylammonium methyl 3-hydroxy-2,3-dimethyl butyl-2-phosphate (D_2O solution, 500 cps sweep width). Peak at 8.62 τ is due to cyclohexylammonium pinacol phosphate contaminant (see text).

Kinetic Studies

Tri-t-butyl Phosphate

Solutions for basic solvolysis of tri-t-butyl phosphate were prepared in each case by the following method.

A quantity of a standard solution of sodium hydroxide was pipetted into a volumetric flask and a proportional quantity of the second solvent (ethanol or 1,2-dimethoxyethane) was then added with a pipette in order to achieve the correct solvent ratio. The calculated amount of sodium perchlorate was added in order to adjust the ionic strength to the desired value. The flask was then filled with solvent of the correct ratio. Except for the kinetic runs in 50% 1,2-dimethoxyethane-water, which were carried out in the volumetric flask, a quantity of the solution was pipetted into a polyethylene bottle. The containers were then equilibrated in a 60° temperature bath (all runs on tri-t-butyl phosphate were done at 60°C). After temperature equilibration had been achieved, a quantity of tri-t-butyl phosphate was added. The quantity of ester used was determined by the amount of base present; in most cases the concentration of ester was less than the concentration of base. A 4.00-ml. aliquot was removed immediately after mixing, diluted with water, and titrated to neutrality with standard hydrochloric acid. Since the time lag between mixing and titration was usually less than 60 seconds, this point was considered the point at $t = 0$ and was later used in calculating the infinity value. Aliquot portions were again removed at various time intervals and titrated to neutrality. The infinity value was calculated from the expression

$$ml_i = \left(\frac{ml_o \times N_a \times V}{A} - M \right) \frac{A}{N_a V} \qquad \text{(Eq. 1)}$$

which reduces to

$$ml_i = ml_o - \frac{M \times A}{N_a V} \qquad \text{(Eq. 2)}$$

where ml_i = milliliters of acid required after complete reaction; N_a = normality of hydrochloric acid; V = total volume of solution (ml.); A = volume of an aliquot portion (ml.); M = milliequivalents of ester; ml_o = milliliters of acid required at t = 0.

A first-order dependence of rate of reaction on the concentration of ester is given by the differential equation

$$-\frac{d[E]}{dt} = k[E] \qquad \text{(Eq. 3)}$$

where [E] = concentration of ester; t = time, and k = proportionality constant. Rearrangement integration of the equation gives

$$-\int_{E_o}^{E} \frac{d[E]}{[E]} = k \int_{o}^{t} dt \qquad \text{(Eq. 4)}$$

$$-\ln [E] - \ln [E_o] = - kt \qquad \text{(Eq. 5)}$$

Assuming that one equivalent of base is used up for each equivalent of ester reacted and that loss of base is concurrent with, or follows rapidly, the reaction of the ester, it is obvious that the amount of base lost is the same value as the amount of ester reacted. Furthermore, the

concentration of base is related to the number of milliliters of standard acid required for neutralization by

$$N_b = \frac{ml_a \times N_a}{ml_b} . \qquad \text{(Eq. 6)}$$

where N_b = normality of base, ml_b = A.

Since N_a and ml_b are constant, then

$$N_b \propto ml_a \qquad \text{(Eq. 7)}$$

and

$$[E]_t = N_{b_t} - N_i \qquad \text{(Eq. 8)}$$

where N_i = normality of base after complete reaction.

Thus

$$[E] \propto ml_t - ml_i . \qquad \text{(Eq. 9)}$$

Substituting Eq. 4 into Eq. 5, the following expression is obtained

$$\ln (ml_t - ml_i) - \ln (ml_o - ml_i) = - kt.$$

Plotting $\ln (ml_t - ml_i)$ *vs.* t should give a straight line of slope (-k) if the reaction is first order in ester.

Plots of log $(ml_t - ml_i)$ *vs.* time were constructed from these data. A good fit to a straight line was observed in all cases. Occasionally, after long periods of reaction time, points would deviate because of solvent evaporation, since a tight seal of the polyethylene bottles in every case could not be achieved.

Initially, in order to obtain working numbers quickly, the best straight line fit was drawn visually. The half-life was obtained by subtracting 0.3 from the ordinate value, log $(ml_t - ml_i)$, at t = 0, and finding the value of time with which this value corresponded. Using the relation for a first-order reaction

$$\ln 2 = kt_{1/2} \qquad \text{(Eq. 10)}$$

the rate constant was obtained from the half-life.

Later, a least squares treatment of the data was administered by means of an extended Algol computer program written for the Burroughs' B5500 computer. The results of these calculations are given in Tables 4 through 12. Tables 4 through 12 contain information regarding quantities used in preparing the solutions for each run, and also listed are the measured times and milliliters of titrant required. The quantity ln $(ml_t - ml_i)$ is given also, as well as comparison values of ln $(ml_t - ml_i)$ calculated from the least squares rate constant and intercept. Table 13 is a collection of the half-life, rate constant, and ionic strength for each individual run.

Table 4. Solvolysis of Tri-t-butyl Phosphate in 50% Dimethoxyethane-water at 60°C.

1. 8.00 ml. 1.000 N NaOH/100 ml. 50% DME-water.
5.1425 g. $NaClO_4$/100 ml. solvent.
1.0002 g. TBP/100 ml. solvent.
4.00-ml. aliquots titrated with 0.0484 N HCl.

Time (hrs.)	ml. HCl.	Observed ln(ml.-ml.)	Calculated ln(ml.-ml.)
0.00	6.60	1.13	1.11
3.00	5.70	0.79	0.79
6.00	5.05	0.44	0.47
10.00	4.53	0.03	0.04
13.75	4.20	-0.35	-0.37
$ml._i$	3.50	----	----

$k = 2.99 \times 10^{-5}$ sec^{-1}

2. 8.00 ml. 1.000 N NaOH/50 ml. solvent.
2.0815 g. $NaClO_4$/50 ml. solvent.
1.0170 g. TBP/50 ml. solvent.
4.00 ml. aliquots titrated with 0.0484 N HCl.

Time (hrs.)	$ml._t$	Observed $\ln(ml._t - ml._i)$	Calculated $\ln(ml._t - ml._i)$
0.00	13.10	1.84	1.83
3.00	11.55	1.56	1.57
6.00	10.54	1.32	1.31
10.00	9.35	0.94	0.97
14.00	8.70	0.65	0.63
$ml._i$	6.79	----	----

$k = 2.38 \times 10^{-5}$ sec^{-1}

3. 8.00 ml. 1.000 N NaOH/50 ml. solvent.
0.2442 g. $NaClO_4$/50 ml. solvent.
1.0187 g. TBP/50 ml. solvent.
4.00-ml aliquots titrated with 0.048 N HCl.

Time (hrs.)	$ml._t$	Observed $\ln(ml._t - ml._i)$	Calculated $\ln(ml._t - ml._i)$
0.00	12.82	1.84	1.85
3.00	11.50	1.61	1.62
6.00	10.55	1.40	1.39
10.00	9.50	1.10	1.08
14.25	8.60	0.74	0.76
ml_i	6.50	----	----

$k = 2.13 \times 10^{-5}$ sec^{-1}

Table 5. Solvolysis of Tri-t-butyl Phosphate in 40% Ethanol-water at 60°C.

1. 6.00 ml. 1.000 N NaOH/100 ml. solvent.
2.3264 g. $NaClO_4$/100 solvent.
50 ml. of solution transferred to a polyethylene bottle.
0.5094 g. TBP added to 50 ml. of above solution at 60°C.
4.00-ml. aliquots titrated with 0.0506 N HCl.

Time (min.)	$ml._t$	Observed $\ln(ml._t - ml._i)$	Calculated $\ln(ml._t - ml._i)$
0.00	4.46	1.11	1.11
40.0	4.08	0.97	0.96
73.0	3.75	0.84	0.84
95.0	3.58	0.76	0.75
132.0	3.27	0.61	0.61
193.0	2.85	0.35	0.38
255.0	2.63	0.18	0.15
622.0	1.80	----	----
ml_i	1.44	----	----

$k = 6.28 \times 10^{-5}$ sec^{-1}

2. 6.00 ml. 1.000 N NaOH/100 ml. solvent.
2.3266 g. $NaClO_4$/100 ml. solvent.
50 ml. solution transferred to polyethylene bottle.
0.5290 g. TBP added to 50 ml. of above solution at 60°C.
4.00-ml. aliquots titrated with 0.0506 N HCl.

Time (min.)	$ml._t$	Observed $\ln(ml._t - ml._i)$	Calculated $\ln(ml._t - ml._i)$
0.00	4.53	1.14	1.14
48.0	3.96	0.94	0.94
80.0	3.65	0.82	0.82
106.0	3.50	0.75	0.71
138.0	3.10	0.54	0.58
199.0	2.76	0.32	0.34
255.0	2.55	0.15	0.12
631.0	1.75	----	----
$ml._i$	1.39	----	----

$k = 6.66 \times 10^{-5}$ sec^{-1}

3. 12 ml. of 1.000 N NaOH/100 ml. solvent.
4.6528 g. $NaClO_4$/100 ml. solution.
50 ml. solution transferred to a polyethylene bottle.
0.4768 g. TBP added to 50 ml. of above solution at 60°C.
4.00-ml. aliquots titrated with 0.020 N HCl.

Time (min.)	$ml._t$	Observed $\ln(ml._t - ml._i)$	Calculated $\ln(ml._t - ml._i)$
3.00	23.18	1.96	1.95
30.00	22.30	1.83	1.84
60.00	21.71	1.73	1.72
94.00	20.90	1.58	1.58
123.00	20.37	1.47	1.47
173.00	19.50	1.24	1.26
211.00	19.07	1.14	1.11
256.00	18.59	0.94	0.93
$ml._i$	16.02	----	----

$k = 6.77 \times 10^{-5}$ sec^{-1}

4. 12 ml. of 1.000 N NaOH/100 ml. solvent.
4.6538 g. $NaClO_4$/100 ml. solution.
50 ml. solution transferred to a polyethylene bottle.
0.5124 g. TBP added to 50 ml. of above solution at 60°C.
4.00-ml. aliquots titrated with 0.020 N HCl.

Time (min.)	$ml._t$	Observed $\ln(ml._t - ml._i)$	Calculated $\ln(ml._t - ml._i)$
2.00	22.80	4.04	2.04
28.00	22.01	1.93	1.94
57.00	21.38	1.84	1.84
91.00	20.70	1.72	1.71
119.00	20.18	1.62	1.61
170.00	19.09	1.38	1.42
207.00	18.75	1.29	1.28
253.00	18.17	1.12	1.11
$ml._i$	15.10	----	----

$k = 6.13 \times 10^{-5}$ sec^{-1}

Table 6. Solvolysis of Tri-t-butyl Phosphate in 50% Ethanol-water at 60°C.

1. 10.00 ml. 1.000 N NaOH/100 ml. of solvent.
50 ml. transferred to a polyethylene bottle.
2.4478 g. $NaClO_4$/ro ml. solvent.
0.5213 g. TBP added to 50 ml. of above solution at 60°C.
4.00-ml. aliquots titrated with 0.056 N HCl.

Time (min.)	$ml._t$	Observed $\ln(ml._t - ml._i)$	Calculated $\ln(ml._t - ml._i)$
0.0	7.32	1.13	1.10
2.16	6.54	0.84	0.87
4.08	6.14	0.65	0.68
6.33	5.83	0.47	0.44
7.92	5.55	0.28	0.28
$ml._i$	4.22	----	----

$k = 2.86 \times 10^{-5}$ sec^{-1}

2. 8.00 ml. 1.000 N NaOH/100 ml. solvent.
50 ml. transferred to a polyethylene bottle.
2.5718 g. $NaClO_4$/50 ml. solution.
0.5347 g. TBP added to 50 ml. of above solution at 60°C.
4.00-ml. aliquots titrated with 0.0506 N HCl.

Time (min.)	$ml._t$	Observed $\ln(ml._t - ml._i)$	Calculated $\ln(ml._t - ml._i)$
0.0	5.70	1.16	1.16
2.08	4.98	0.90	0.94
4.00	4.73	0.79	0.73
6.25	4.20	0.52	0.50
7.84	3.87	0.30	0.33
$ml._i$	2.53	----	----

$k = 2.93 \times 10^{-5}$ sec^{-1}

3. 30.00 ml. 1.000 N NaOH/250 ml. solvent.
11.6329 g. $NaClO_4$/250 ml. solvent.
50 ml. solution transferred to a polyethylene bottle.
0.5102 g. TBP added to 50 ml. of above solution at 60°C.
4.00-ml. aliquots titrated with 0.0506 N HCl.

Time (min.)	$ml._t$	Observed $\ln(ml._t - ml._i)$	Calculated $\ln(ml._t - ml._i)$
0.0	8.95	1.11	1.09
2.08	8.26	0.85	0.89
4.16	7.97	0.72	0.69
6.25	7.55	0.49	0.48
7.92	7.29	0.31	0.32
$ml._i$	5.92	----	----

$k = 2.70 \times 10^{-5}$ sec^{-1}

4. 30.00 ml. 1.000 N NaOH/250 ml. solvent.
11.6329 g. $NaClO_4$/250 ml. solution.
50 ml. solution transferred to polyethylene bottle.
1.0007 g. TBP added to 50 ml. of above solution at 60°C.
4.00-ml. aliquots titrated with 0.0506 N HCl.

Time (min.)	$ml._t$	Observed $\ln(ml._t - ml._i)$	Calculated $\ln(ml._t - ml._i)$
0.0	8.60	1.78	1.78
2.08	7.41	1.56	1.56
4.08	6.57	1.36	1.35
6.16	5.57	1.13	1.13
7.84	5.25	0.95	0.96
$ml._i$	2.66	----	----

$k = 2.93 \times 10^{-5}$ sec^{-1}

5. 4.00 ml. 1.000 N NaOH/100 ml. solvent.
5.6323 g. $NaClO_4$/100 ml. solution.
50 ml. solution transferred to a polyethylene bottle.
0.4304 g. TBP added to 50 ml. of above solution at 60°C.
4.00-ml. aliquots titrated with 0.0495 N HCl.

Time (min.)	$ml._t$	Observed $\ln(ml._t - ml._i)$	Calculated $\ln(ml._t - ml._i)$
0.0	3.07	0.96	0.96
1.08	2.74	0.83	0.82
2.03	2.48	0.70	0.69
3.00	2.20	0.55	0.56
8.00	1.33	-0.14	-0.10
9.00	1.23	-0.26	-0.23
10.00	1.15	-0.37	-0.37
11.00	1.07	-0.49	-0.50
12.00	1.01	-0.59	-0.63
$ml._i$	0.46	----	----

$k = 3.68 \times 10^{-5}$ sec^{-1}

6. 8.00 ml. 1.000 N NaOH/100 ml. solvent.
5.1430 g. $NaClO_4$/100 ml. solution.
50 ml. solution transferred to a polyethylene bottle.
0.9293 g. TBP added to 50 ml. of above solution at 60°C.
4.00-ml. aliquots titrated with 0.0495 N HCl.

Time (min.)	$ml._t$	Observed $\ln(ml._t - ml._i)$	Calculated $\ln(ml._t - ml._i)$
0.00	6.21	1.73	1.73
1.03	5.55	1.61	1.60
1.93	4.96	1.48	1.49
2.93	4.48	1.36	1.36
7.93	2.61	0.71	0.73
8.93	2.41	0.61	0.60
9.93	2.16	0.46	0.48
10.93	2.00	0.36	0.35
11.93	1.84	0.24	0.23
$ml._i$	0.57	----	----

$k = 3.49 \times 10^{-5}$ sec^{-1}

7. 16.00 ml. 1.000 N NaOH/100 ml. solvent.
4.1636 g. $NaClO_4$/100 ml. solvent.
50 ml. solution transferred to a polyethylene bottle.
1.9485 g. TBP added to 50 ml. of above solution at 60°C.
4.00-ml. aliquots titrated with 0.0495 N HCl.

Time (min.)	$ml._t$	Observed $\ln(ml._t - ml._i)$	Calculated $\ln(ml._t - ml._i)$
0.00	12.25	2.47	2.48
1.00	11.24	2.38	2.37
2.00	10.17	2.28	2.27
3.00	9.11	2.16	2.16
7.00	6.02	1.72	1.74
8.00	5.52	1.63	1.63
9.00	5.01	1.52	1.53
10.10	4.52	1.41	1.41
11.00	4.18	1.32	1.31
$ml._i$	0.42	----	----

$k = 2.94 \times 10^{-5} sec^{-1}$

8. 20.00 ml. 1.000 N NaOH/100 ml. solvent.
3.6737 g. $NaClO_4$/100 ml. solution.
50 ml. transferred to a polyethylene bottle.
2.3067 g. TBP added to 50 ml. of above solution at 60°C.
4.00-ml. aliquots titrated with 0.0495 N HCl.

Time (min.)	$ml._t$	Observed $\ln(ml._t - ml._i)$	Calculated $\ln(ml._t - ml._i)$
0.00	15.35	2.64	2.62
1.00	13.78	2.52	2.52
2.00	12.52	2.42	2.42
3.00	11.53	2.32	2.33
7.00	8.18	1.92	1.93
8.00	7.57	1.83	1.83
9.00	6.95	1.72	1.73
10.00	6.48	1.63	1.63
11.00	5.96	1.53	1.53
$ml._i$	1.35	----	----

$k = 2.77 \times 10^{-5}$ sec^{-1}

9. 4.00 ml. 1.000 N NaOH/100 ml. solvent.
5.6323 g. $NaClO_4$/100 ml. solution.
50 ml. solution transferred to a polyethylene bottle.
0.4304 g. TBP added to 50 ml. of above solution at 60°C.
4.00-ml. aliquots titrated with 0.0495 N HCl.

Time (min.)	$ml._t$	Observed $\ln(ml._t - ml._i)$	Calculated $\ln(ml._t - ml._i)$
0.00	2.72	0.96	0.97
1.30	2.36	0.81	0.82
2.40	2.13	0.70	0.69
3.23	1.95	0.61	0.60
4.23	1.74	0.49	0.48
5.23	1.56	0.37	0.37
6.23	1.37	0.23	0.25
11.30	0.94	----*	----
12.30	0.81	----*	----
13.23	0.75	----*	----
$ml._i$	0.11	----	----

$k = 3.20 \times 10^{-5}$ sec^{-1}

* These points were not used in the calculation of the least squares rate constant.

10. 8.00 ml. 1.000 N NaOH/100 ml. solvent.
5.1430 g. $NaClO_4$/100 ml. solution.
50 ml. transferred to a polyethylene bottle.
0.9293 g. TBP added to 50 ml. of above solution at 60°C.
4.00-ml. aliquots titrated with 0.0495 N HCl.

Time (min.)	$ml._t$	Observed $\ln(ml._t - ml._i)$	Calculated $\ln(ml._t - ml._i)$
0.00	5.76	1.73	1.71
1.27	5.05	1.60	1.58
2.37	4.46	1.47	1.46
3.20	4.03	1.36	1.37
4.20	3.68	1.27	1.27
5.20	3.24	1.14	1.16
6.20	2.93	1.03	1.06
11.55	1.77	0.50	0.49
12.25	1.65	0.43	0.41
$ml._i$	0.12	----	----

$k = 2.95 \times 10^{-5}$ sec^{-1}

11. 16.00 ml. 1.000 N NaOH/100 ml. solvent.
4.1636 g. $NaClO_4$/100 ml. solution.
50 ml. transferred to a polyethylene bottle.
1.9485 g. TBP added to 50 ml. of above solution at 60°C.
4.00-ml. aliquots titrated with 0.0495 N HCl.

Time (min.)	$ml._t$	Observed $\ln(ml._t - ml._i)$	Calculated $\ln(ml._t - ml._i)$
0.00	11.01	2.47	2.46
1.20	9.85	2.37	2.35
2.30	8.69	2.25	2.25
3.13	7.91	2.17	2.17
4.13	7.10	2.07	2.08
5.13	6.41	1.98	1.99
6.13	5.71	1.88	1.90
11.22	3.33	1.42	1.43
12.18	3.05	1.35	1.34
13.13	2.74	1.27	1.25
$ml._i$	-0.82	----	----

$k = 2.55 \times 10^{-5}$ sec^{-1}

12. 20.00 ml. 1.000 N NaOH/100 ml. solvent.
3.6737 g. $NaClO_4$/100 ml. solution.
50 ml. transferred to a polyethylene bottle.
2.3067 g. TBP added to 50 ml. of above solution at 60°C.
4.00-ml. aliquots titrated with 0.0495 N HCl.

Time (min.)	$ml._t$	Observed $\ln(ml._t - ml._i)$	Calculated $\ln(ml._t - ml._i)$
0.00	13.80	2.64	2.64
1.13	12.62	2.55	2.54
2.25	11.27	2.44	2.44
3.07	10.46	2.37	2.37
4.08	9.60	2.28	2.29
5.08	8.79	2.20	2.20
6.07	8.05	2.11	2.11
11.15	5.04	1.66	1.68
12.12	4.80	1.61	1.59
13.08	4.37	1.52	1.51
$ml._i$	-0.20	----	----

$k = 2.39 \times 10^{-5}$ sec^{-1}

Table 7. Solvolysis of Tri-t-butyl Phosphate in 60% Ethanol-water at 60°C.

1. 10.00 ml. 1.000 N NaOH/100 ml. solvent.
4.8181 g. $NaClO_4$/100 ml. solution.
50 ml. transferred to a polyethylene bottle.
0.5318 g. TBP added to 50 ml. of above solution at 60°C.
4.00-ml. aliquots titrated with 0.495 N HCl.

Time (min.)	$ml._t$	Observed $\ln(ml._t - ml._i)$	Calculated $\ln(ml._t - ml._i)$
0.00	7.75	1.17	1.17
1.42	7.51	1.09	1.09
3.88	7.10	0.95	0.95
8.23	6.58	0.72	0.71
10.75	6.27	0.56	0.57
$ml._i$	4.52	----	----

$k = 1.57 \times 10^{-5}$ sec^{-1}

2. 10.00 ml. 1.000 N NaOH/100 ml. solution.
4.8981 g. $NaClO_4$/100 ml. solution.
50 ml. transferred to a polyethylene bottle.
0.4970 g. TBP added to 50 ml. of above solution at 60°C.
4.00-ml. aliquots titrated with 0.0495 N HCl.

Time (min.)	$ml._t$	Observed $\ln(ml._t - ml._i)$	Calculated $\ln(ml._t - ml._i)$
0.00	7.61	1.10	1.10
1.30	7.33	1.01	1.00
3.72	6.86	0.82	0.83
8.13	6.26	0.51	0.51
$ml._i$	4.59	----	----

$k = 2.03 \times 10^{-5}$ sec^{-1}

Table 8. Solvolysis of Tri-t-butyl Phosphate in 70% Ethanol-water at 60°C.

1. 9.00 ml. 1.000 N NaOH/100 ml. solvent.
5.0210 g. $NaClO_4$/100 ml. solution.
50 ml. solution transferred to a polyethylene bottle.
0.6369 g. TBP added to 50 ml. of above solution at 60°C.
4.00-ml. aliquots titrated with 0.0493 N HCl.

Time (min.)	$ml._t$	Observed $\ln(ml._t - ml._i)$	Calculated $\ln(ml._t - ml._i)$
0.00	7.26	1.36	1.36
4.52	6.68	1.19	1.18
9.75	6.01	0.97	0.97
14.87	5.79	----*	----
15.53	5.79	----*	----
22.32	5.67	----*	----
$ml._i$	3.38	----	----

$k = 1.11 \times 10^{-5}$ sec^{-1}

* These values were not used in calculation of least squares rate constant.

2. 9.00 ml. 1.000 N NaOH/100 ml. solvent.
5.0206 g. $NaClO_4$/100 ml. solution.
50 ml. transferred to a polyethylene bottle.
0.5160 g. TBP added to 50 ml. of above solution at 60°C.
4.00-ml. aliquots titrated with 0.0493 N HCl.

Time (min.)	$ml._t$	Observed $\ln(ml._t - ml._i)$	Calculated $\ln(ml._t - ml._i)$
0.00	6.98	1.15	1.15
4.33	6.53	0.99	0.99
9.53	6.03	0.79	0.80
14.62	5.68	0.61	0.61
22.13	5.23	0.33	0.33
$ml._i$	3.84	----	----

$k = 1.02 \times 10^{-5}$ sec^{-1}

3. 9.00 ml. 1.000 N NaOH/100 ml. solvent.
5.0203 g. $NaClO_4$/100 ml. solution.
50 ml. transferred to a polyethylene bottle.
0.4023 g. TBP added to 50 ml. of above solution at 60°C.
4.00-ml. aliquots titrated with 0.0493 N HCl.

Time (min.)	$ml._t$	Observed $\ln(ml._t - ml._i)$	Calculated $\ln(ml._t - ml._i)$
0.00	6.91	0.90	0.90
4.23	6.63	0.78	0.76
9.38	6.25	0.58	0.59
14.45	5.97	0.41	0.41
21.93	5.72	----*	----
$ml._i$	4.46	----	----

$k = 0.943 \times 10^{-5}$ sec^{-1}

* This value was not used in calculating least squares rate constant.

Table 9. Solvolysis of Tri-t-butyl Phosphate in 80% Ethanol-water at 60°C.

1. 8.00 ml. 1.000 N NaOH/100 ml. solvent.
5.1423 g. $NaClO_4$/100 ml. solution.
50 ml. transferred to a polyethylene bottle.
0.5162 g. TBP added to 50 ml. of above solution at 60°C.
4.00-ml. aliquots titrated with 0.0493 N HCl.

Time (min.)	$ml._t$	Observed $\ln(ml._t - ml._i)$	Calculated $\ln(ml._t - ml._i)$
0.00	6.14	1.15	1.16
3.65	5.97	1.09	1.09
6.78	5.79	1.02	1.03
10.43	5.64	0.97	0.96
13.75	5.45	0.90	0.90
25.42	5.01	0.70	0.69
35.35	4.63	0.49	0.50
$ml._i$	2.99	----	----

$k = 0.512 \times 10^{-5}$ sec^{-1}

2. 8.00 ml. 1.000 N NaOH/100 ml. solvent.
5.1434 g. $NaClO_4$/100 ml. solvent.
50 ml. transferred to a polyethylene bottle.
0.6389 g. TBP added to 50 ml. of above solution at 60°C.
4.00-ml. aliquots titrated with 0.0493 N HCl.

Time (min.)	$ml._t$	Observed $\ln(ml._t - ml._i)$	Calculated $\ln(ml._t - ml._i)$
0.00	6.13	1.36	1.36
3.67	5.87	1.29	1.29
6.82	5.66	1.23	1.23
10.42	5.43	1.16	1.16
13.80	5.23	1.10	1.10
25.47	4.65	0.88	0.88
35.40	4.24	0.69	0.69
$ml._i$	2.24	----	----

$k = 0.521 \times 10^{-5}$ sec^{-1}

3. 8.00 ml. 1.000 N NaOH/100 ml. solvent.
5.1426 g. $NaClO_4$/100 ml. solution.
50 ml. transferred to a polymethylene bottle.
0.5467 g. TBP added to 50 ml. of above solution at 60°C.
4.00 ml. aliquots titrated with 0.0493 N HCl.

Time (min.)	$ml._t$	Observed $\ln(ml._t - ml._i)$	Calculated $\ln(ml._t - ml._i)$
0.00	6.10	1.20	1.20
3.62	5.92	1.15	1.14
6.73	5.76	1.10	1.09
10.38	5.50	1.00	1.02
13.70	5.40	0.97	0.96
25.40	4.87	0.74	0.76
35.32	4.58	0.59	0.58
$ml._i$	2.77	----	----

$k = 0.489 \times 10^{-5}$ sec^{-1}

Table 10. Solvolysis of Tri-t-butyl Phosphate in 90% Ethanol-water at 60°C.

1. 2.00 ml. 4.004 N NaOH/100 ml. solvent.
5.1314 g. $NaClO_4$/100 ml. solution.
50 ml. transferred to a polyethylene bottle.
0.7002 g. TBP added to 50 ml. of above solution at 60°C.
4.00 ml. aliquots titrated with 0.0495 N HCl.

Time (min.)	$ml._t$	Observed $\ln(ml._t - ml._i)$	Calculated $\ln(ml._t - ml._i)$
0.00	6.10	1.45	1.47
6.53	5.99	1.42	1.42
17.93	5.65	1.33	1.32
29.30	5.25	1.22	1.23
43.55	4.95	1.13	1.11
51.43	4.69	1.04	1.04
77.25	4.10	0.81	0.82
89.05	3.91	0.72	0.73
$ml._i$	1.85	----	----

$k = 0.232 \times 10^{-5}$ sec^{-1}

2. 2.00 ml. 4.044 N NaOH/100 ml. solvent.
5.1319 g. $NaClO_4$/100 ml. solution.
50 ml. transferred to a polyethylene bottle.
0.5884 g. TBP added to 50 ml. of above solution at 60°C.
4.00-ml. aliquots titrated with 0.0495 N HCl.

Time (min.)	$ml._t$	Observed $\ln(ml._t - ml._i)$	Calculated $\ln(ml._t - ml._i)$
0.00	6.16	1.27	1.29
6.50	6.10	1.26	1.23
17.90	5.67	1.13	1.13
29.22	5.38	1.03	1.04
43.50	5.07	0.91	0.91
51.38	4.97	0.87	0.85
77.20	4.42	0.60	0.62
89.00	2.49	0.53	0.52
$ml._i$	2.59	----	----

$k = 0.239 \times 10^{-5}$ sec^{-1}

3. 2.00 ml. 4.044 N NaOH/100 ml. solvent.
5.1320 g. $NaClO_4$/100 ml. solution.
50 ml. of solution transferred to a polyethylene bottle.
0.5564 g. TBP added to 50 ml. of above solution at 60°C.
4.00-ml. aliquots titrated with 0.0495 N HCl.

Time (min.)	$ml._t$	Observed $\ln(ml._t - ml._i)$	Calculated $\ln(ml._t - ml._i)$
0.00	6.10	1.22	1.24
6.45	6.00	1.19	1.19
17.92	5.76	1.11	1.09
29.17	5.38	0.98	1.00
43.50	5.14	0.88	0.88
51.32	5.08	0.86	0.82
77.15	4.55	0.60	0.60
88.95	5.35	0.49	0.51
$ml._i$	3.15	----	----

$k = 0.228 \times 10^{-5}$ sec^{-1}

Table 11. Solvolysis of Tri-t-butyl Phosphate in 50% Ethanol-water at 60°C.: Added Cyclohexylammonium di-t-Butyl Phosphate.

1. 16.00 ml. 1.000 N NaOH/100 ml. solvent.
2.4564 g. $NaClO_4$/100 ml. solution.
4.3316 g. cyclohexylammonium di-t-butyl phosphate/100 ml. solution.
50 ml. of solution transferred to a polyethylene bottle.
1.8480 g. tri-t-butyl phosphate added to 50 ml. of above solution at 60°C.
4.0-ml. aliquots titrated with 0.0494 N HCl.

Time (hrs.)	$ml._t$	Observed $\ln(ml._t - ml._i)$	Calculated $\ln(ml._t - ml._i)$
0.00	11.64	2.42	2.42
1.25	10.65	2.33	2.32
2.25	9.65	2.22	2.23
3.25	9.03	2.15	2.15
4.25	8.28	2.06	2.06
5.25	7.58	1.97	1.98
6.25	7.05	1.89	1.89
7.25	6.49	1.81	1.81
10.25	5.11	1.55	1.55
$ml._i$	0.40	----	----

$k = 2.37 \times 10^{-5}$ sec^{-1}

Table 12. Solvolysis of Tri-t-butyl Phosphate in 50% Ethanol-water at 60°C.: Cyclohexylamine as base.

1. 0.8810 g. cyclohexylamine/250 ml. solvent.
Solution transferred to a polyethylene bottle.
2.0775 g. TBP added to 50 ml. of above solution at 60°C.
4-ml. aliquots titrated with 0.0495 N HCl.

Time	$ml._t$	Observed $\ln(ml._t - ml._i)$	Calculated $\ln(ml._t - ml._i)$
0.00	2.60	0.81	0.85
0.88	2.46	0.74	0.
1.28	2.36	0.70	0.69
1.97	2.22	0.62	0.61
3.05	2.01	0.50	0.48
4.10	1.80	0.37	0.35
5.33	1.56	0.19	0.20
6.20	1.03	-0.39	-0.39
$ml._i$	0.36	----	----

$k = 3.36 \times 10^{-5}$ sec^{-1}

Table 13. Rate Constants for Solvolysis of Tri-t-butyl Phosphate in Various Solvents.

Solvent	Conc. Ester	Conc. Base	Half-life (hrs.)	k x 10^5 sec^{-1}	Ionic strength	Y[c]
50% DME H_2O	0.0376	0.0799	6.43	2.99	0.500	-----
"	0.0764	0.1585	8.07	2.38	0.498	-----
"	0.0765	0.1551	906	2.13	0.195	-----
40% EtOH H_2O	0.0383	0.0564	3.06	6.28	0.246	2.196
"	0.0397	0.0573	2.89	6.66	0.247	"
"	0.0358	0.1159	2.84	6.76	0.496	"
"	0.0385	0.1140	3.14	6.13	0.494	"
50% EtOH H_2O	0.0392	0.0926	6.73	2.86	0.492	1.655
"	0.0402	0.0721	6.56	2.93	0.492	"
"	0.0383	0.1132	7.12	2.70	0.493	"
"	0.0752	0.1088	6.58	2.93	0.489	"
"	0.0323	0.0380	5.23	3.68	0.498	"
"	0.0698	0.0768	5.50	3.50	0.497	"
"	0.1463	0.1516	6.54	2.94	0.492	"
"	0.1732	0.1900	6.95	2.77	0.490	"
"	0.0323	0.0337	6.01	3.20	0.494	"
"	0.0698	0.0713	6.53	2.95	0.491	"
"	0.1463	0.1362	7.56	2.55	0.476	"
"	0.1732	0.1708	8.06	2.39	0.470	"
"	0.0312	0.0322	5.73	3.36	0.032[a]	"
"	0.1388	0.1438	8.12	2.37	0.484[b]	"
60% EtOH H_2O	0.0399	0.0959	12.29	1.57	0.496	1.124
"	0.0373	0.0942	9.49	2.02	0.494	"
70% EtOH H_2O	0.0478	0.0895	17.35	1.11	0.499	0.595
"	0.0388	0.0860	18.85	1.02	0.496	"
"	0.0302	0.0852	20.42	0.94	0.495	"

80% EtOH H_2O	0.0388	0.0757	37.60	0.51	0.496	0.000
"	0.0480	0.0756	36.95	0.52	0.496	"
"	0.0411	0.0752	39.39	0.49	0.495	"
90% EtOH H_2O	0.0526	0.0755	82.81	0.23	0.494	
"	0.0442	0.0762	80.65	0.24	0.495	-0.747
"	0.0418	0.0755	84.33	0.23	0.495	

---

[a] No ionic salt was added in this run; the base used was cyclohexylamine rather than sodium hydroxide.

[b] Solution was made 0.14 N in chclohexylammonium di-t-butyl phosphate.

[c] Grunwald-Winstein Y value for these solvents taken from A. H. Feinberg and S. Winstein, J. Am. Chem. Soc., 78, 2770 (1956).

Tri-i-propyl Phosphate

The method of preparing solutions for rate studies on tri-i-propyl phosphate is the same as the method used with tri-t-butyl phosphate. A quantity of standard sodium hydroxide solution was pipetted into a 100-ml. volumetric flask. Sodium perchlorate was added in sufficient quantity to achieve the desired ionic strength, and the flask was filled to the mark with water. Fifty milliliters of this solution were transferred to a 4-oz. Teflon bottle, and thermostated at 90°C. (At 60°C., the reaction was found to proceed so slowly that rate measurements were not feasible.) After temperature equilibration, a weighed amount of tri-i-propyl phosphate was added. An initial aliquot portion was withdrawn, diluted with water and titrated. This point was later used to calculate the infinity value. (See page 84.) Further aliquot portions were removed at various time intervals and titrated. The data collected were treated in the same manner as those of tri-t-butyl phosphate.

Table 14 lists the collected data, as well as $\ln(ml._t - ml._i)$ which

was observed. The column labeled Calculated $\ln(ml._t - ml._i)$ is the value calculated from the rate constant and intercept calculated by least squares. Table 15 is a collection of the rate constants observed in individual runs.

Table 14. Solvolysis of Tri-i-propyl Phosphate in Water at 90°C.

1. 4.00 ml. of 1.000 N NaOH/100 ml. water.
5.6327 g. $NaClO_4$/100 ml. solution.
50 ml. of solution transferred to a Teflon bottle.
0.4190 g. TPP added to 50 ml. of above solution at 90°C.
5.00-ml. aliquots titrated with 0.0207 N HCl.

Time	$ml._t$	Observed $\ln(ml._t - ml._i)$	Calculated $\ln(ml._t - ml._i)$
0.00	8.90	2.20	2.16
2.05	8.50	2.15	2.14
6.00	7.90	2.08	2.09
20.00	6.60	1.91	1.93
22.00	6.41	1.88	1.91
28.00	5.90	1.80	1.84
45.00	5.15	1.66	1.65
48.00	4.95	1.62	1.61
51.00	4.81	1.60	1.58
$ml._i$	-0.13	----	----

$k = 3.17 \times 10^{-6}$ sec^{-1}

2. 4.00 ml. of 1.000 N NaOH/100 ml. water.
5.6327 g. $NaClO_4$/100 ml. solution.
50 ml. of solution transferred to a Teflon bottle.
0.3782 g. TPP added to 50 ml. of above solution at 90°C.
5.00-ml. aliquots titrated with 0.0207 N HCl.

Time	$ml._t$	Observed $\ln(ml._t - ml._i)$	Calculated $\ln(ml._t - ml._i)$
0.00	8.90	2.10	2.06
2.00	8.60	2.06	2.04
6.00	8.10	1.99	1.99
20.00	6.85	1.81	1.83
22.00	6.65	1.77	1.81
28.00	6.15	1.69	1.74
45.00	5.48	1.55	1.54
48.00	5.29	1.51	1.50
51.00	5.18	1.49	1.46
$ml._i$	0.75	----	----

$k = 3.26 \times 10^{-6}$ sec^{-1}

3. 4.00 ml. of 1.000 N NaOH/100 ml. water.
5.6327 g. $NaClO_4$/100 ml. solution.
50 ml. of solution transferred to a Teflon bottle.
0.3106 g. TPP added to 50 ml. of above solution at 90°C.
5.00-ml. aliquots titrated with 0.0560 N HCl.

Time	$ml._t$	Observed $\ln(ml._t - ml._i)$	Calculated $\ln(ml._t - ml._i)$
0.00	3.31	0.91	0.90
2.00	3.24	0.88	0.87
6.00	3.08	0.80	0.80
18.00	2.62	0.58	0.59
22.00	2.52	0.52	0.53
26.00	2.40	0.45	0.46
42.00	2.03	0.18	0.18
46.00	1.97	0.13	0.11
49.00	1.91	0.07	0.06
$ml._i$	0.84	----	----

$k = 4.76 \times 10^{-6}$ sec^{-1}

4. 8.00 ml. of 1.000 N NaOH/100 ml. water.
5.1429 g. $NaClO_4$/100 ml. solution.
50 ml. of solution transferred to a Teflon bottle.
0.7480 g. TPP added to 50 ml. of above solution at 90°C.
5.00-ml. aliquots titrated with 0.0560 N HCl.

Time	$ml._t$	Observed $\ln(ml._t - ml._i)$	Calculated $\ln(ml._t - ml._i)$
0.00	6.63	1.78	1.78
2.00	6.44	1.75	1.75
6.00	6.08	1.69	1.68
18.00	5.10	1.49	1.49
22.00	4.80	1.42	1.42
26.00	4.58	1.36	1.36
42.00	3.66	1.09	1.10
46.00	3.48	1.03	1.03
49.00	3.37	0.99	0.98
$ml._i$	0.67	----	----

$k = 4.53 \times 10^{-6}$ sec^{-1}

5. 16.00 ml. of 1.000 N NaOH/100 ml. water.
4.1650 g. $NaClO_4$/100 ml. solution.
50 ml. solution transferred to a Teflon bottle.
1.6452 g. TPP added to 50 ml. of above solution at 90°C.
5.00-ml. aliquots titrated with 0.0560 N HCl.

Time	$ml._t$	Observed $\ln(ml._t - ml._i)$	Calculated $\ln(ml._t - ml._i)$
0.00	13.35	2.57	2.58
2.00	13.15	2.56	2.56
6.00	12.74	2.52	2.52
18.00	11.48	2.42	2.41
22.00	11.10	2.38	2.38
26.00	10.68	2.34	2.34
42.00	9.19	2.19	2.16
46.00	8.84	2.15	2.16
$ml._i$	0.25	----	----

$k = 2.55 \times 10^{-6}$ sec^{-1}

6. 4.00 ml. of 1.000 N NaOH/100 ml. water.
5.6327 g. $NaClO_4$/100 ml. solution.
50 ml. of Solution transferred to a Teflon bottle.
0.3136 g. TPP added to 50 ml. of above solution at 90°C.
5.00-ml. aliquots titrated with 0.0560 N HCl.

Time	$ml._t$	Observed $\ln(ml._t - ml._i)$	Calculated $\ln(ml._t - ml._i)$
0.00	3.36	0.91	0.87
7.50	3.03	0.77	0.75
16.00	2.67	0.59	0.61
18.00	2.58	0.54	0.57
22.00	2.50	0.49	0.51
28.00	2.32	0.38	0.41
41.00	2.07	0.19	0.19
73.50	1.58	-0.33	-0.36
$ml._i$	0.86	----	----

$k = 4.65 \times 10^{-6}$ sec^{-1}

7. 8.00 ml. of 1.000 N NaOH/100 ml. water.
5.1429 g. $NaClO_4$/100 ml. solution.
50 ml. of solution transferred to a Teflon bottle.
0.7600 g. TPP added to 50 ml. of above solution at 90°C.
5.00-ml. aliquots titrated with 0.0560 N HCl.

Time	$ml._t$	Observed $\ln(ml._t - ml._i)$	Calculated $\ln(ml._t - ml._i)$
0.00	6.71	1.80	1.79
7.50	6.02	1.68	1.67
16.00	5.27	1.53	1.53
18.00	5.13	1.50	1.50
22.00	4.87	1.44	1.44
28.00	4.47	1.34	1.35
41.00	3.75	1.13	1.14
73.50	2.57	0.65	0.63
$ml._i$	0.66	----	----

$k = 4.35 \times 10^{-6}$ sec^{-1}

8. 16.00 ml. of 1.000 N NaOH/100 ml. water.
4.1650 g. $NaClO_4$/100 ml. solution.
50 ml. of solution transferred to a Teflon bottle.
1.6397 g. TPP added to 50 ml. of above solution at 90°C.
5.00-ml. aliquots titrated with 0.0560 N HCl.

Time	$ml._t$	Observed $\ln(ml._t - ml._i)$	Calculated $\ln(ml._t - ml._i)$
0.00	13.37	2.57	2.59
7.50	12.55	2.50	2.51
16.00	11.65	2.43	2.43
18.00	11.51	2.42	2.41
22.00	11.05	2.37	2.37
28.00	10.50	2.32	2.31
41.00	9.36	2.20	2.18
73.50	6.62	1.84	1.86
$ml._i$	0.31	----	----

$k = 2.75 \times 10^{-6}$ sec^{-1}

9. 2.00 ml. of 1.000 N NaOH/100 ml. water.
5.8800 g. $NaClO_4$/100 ml. solution.
50 ml. of solution transferred to a Teflon bottle.
0.1984 g. TPP added to 50 ml. of above solution at 90°C.
5.00-ml. aliquots titrated with 0.0113 N HCl.

Time	$ml._t$	Observed $\ln(ml._t - ml._i)$	Calculated $\ln(ml._t - ml._i)$
0.00	8.46	2.06	2.05
1.00	8.31	2.04	2.03
3.00	8.05	2.00	2.00
6.00	7.58	1.94	1.94
21.00	5.94	1.67	1.68
26.00	5.51	1.58	1.60
29.00	5.32	1.54	1.55
45.00	4.24	1.28	1.27
$ml._i$	0.63	----	----

$k = 4.83 \times 10^{-6}$ sec^{-1}

10. 1.00 ml. of 1.000 N NaOH/100 ml. water.
6.0025 g. $NaClO_4$/100 ml. solution.
50 ml. of solution transferred to a Teflon bottle.
0.0860 g. TPP added to 50 ml. of above solution at 90°C.
5.00-ml. aliquots titrated with 0.0113 N HCl.

Time	$ml._t$	Observed $\ln(ml._t - ml._i)$	Calculated $\ln(ml._t - ml._i)$
0.00	4.21	1.22	1.23
1.00	4.07	1.18	1.21
3.00	4.00	1.16	1.16
6.00	3.77	1.08	1.09
21.00	2.95	0.76	0.74
26.00	2.76	0.66	0.62
29.00	2.61	0.58	0.55
45.00	1.94	0.12	0.17
$ml._i$	0.82	----	----

$k = 6.52 \times 10^{-6}$ sec^{-1}

11. 0.50 ml. of 1.000 N NaOH/100 ml. water.
6.0637 g. $NaClO_4$/100 ml. solution.
50 ml. of solution transferred to a Teflon bottle.
0.0336 g. TPP added to 50 ml. of above solution at 90°C.
5.00 ml. aliquots titrated with 0.0113 N HCl.

Time	$ml._t$	Observed $\ln(ml._t - ml._i)$	Calculated $\ln(ml._t - ml._i)$
0.00	2.05	0.28	0.32
1.00	2.03	0.27	0.29
3.00	1.95	0.20	0.24
6.00	1.89	0.15	0.15
21.00	1.55	-0.19	-0.28
26.00	1.42	-0.36	-0.42
29.00	1.37	-0.44	-0.51
45.00	1.06	-1.09	-0.97
$ml._i$	0.72	----	----

$k = 7.98 \times 10^{-6}$ sec^{-1}

12. 8.00 ml. of 1.000 N NaOH/100 ml. water.
5.1429 g. $NaClO_4$/100 ml. solution.
50 ml. of solution transferred to a Teflon bottle.
0.3142 g. TPP added to 50 ml. of above solution at 90°C.
5.00-ml. aliquots titrated with 0.0560 N HCl.

Time	$ml._t$	Observed $\ln(ml._t - ml._i)$	Calculated $\ln(ml._t - ml._i)$
0.00	6.50	0.92	0.87
17.00	6.00	0.69	0.71
20.00	5.90	0.64	0.68
24.00	5.85	0.62	0.64
41.00	5.61	0.48	0.48
45.00	5.55	0.44	0.44
49.00	5.50	0.41	0.40
65.00	5.31	0.27	0.25
$ml._i$	4.00	----	----

$k = 2.64 \times 10^{-6}$ sec^{-1}

13. 16.00 ml. of 1.000 N NaOH/100 ml. water.
4.1650 g. $NaClO_4$/100 ml. solution.
50 ml. of solution transferred to a Teflon bottle.
0.7090 g. TPP added to 50 ml. of above solution at 90°C.
5.00-ml. aliquots titrated with 0.0560 N HCl.

Time	$ml._t$	Observed $\ln(ml._t - ml._i)$	Calculated $\ln(ml._t - ml._i)$
0.00	13.45	1.73	1.70
17.00	11.85	1.40	1.41
20.00	11.73	1.37	1.36
24.00	11.42	1.28	1.30
41.00	10.50	0.99	1.02
45.00	10.35	0.93	0.95
49.00	10.20	0.87	0.88
65.00	9.74	0.66	0.62
$ml._i$	7.80	----	----

$k = 4.60 \times 10^{-6}$ sec^{-1}

Table 15. Rate Constants for Solvolysis of Tri-i-propyl Phosphate in Water at 90°C.

Conc. Ester	Conc. Base	Half-life (hrs.)	k (x 10^6) sec^{-1}	μ
0.0374	0.0368	60.64	3.17	0.497
0.0337	0.0368	58.98	3.26	0.497
0.0277	0.0371	40.45	4.76	0.497
0.0667	0.0743	42.53	4.53	0.494
0.1467	0.1495	75.45	2.55	0.490
0.0280	0.0376	41.42	4.65	0.498
0.0678	0.0752	44.22	4.35	0.495
0.1462	0.1497	70.11	2.75	0.490
0.0177	0.0191	39.90	4.83	0.499
0.0077	0.0095	29.51	6.52	0.500
0.0030	0.0046	24.11	7.98	0.500
0.0280	0.0728	72.89	2.64	0.493
0.0632	0.1506	41.81	4.61	0.491

Triallyl Phosphate

The same procedures were used in following the kinetics of solvolysis of triallyl phosphate that were used with tri-i-propyl and tri-t-butyl phosphates. Identical quantities of 1.000 N NaOH solution and ethanol were added to a volumetric flask. Sodium perchlorate was added to adjust the ionic strength to the desired level. The flask was then filled to the mark with 50% ethanol-water solvent. Fifty milliliters of this solution was transferred to a polyethylene bottle and equilibrated at 60°C in a constant temperature bath. After equilibration, a quantity of triallyl phosphate was introduced and an aliquot sample removed

immediately, quenched with cold water, and titrated with standard hydrochloric acid. This point was considered t = 0 and used to calculate the initial concentration of base. Aliquots were removed at various time intervals, quenched with water, and titrated with standard hydrochloric acid.

Plots of log ($ml._t - ml._i$) *vs.* t, as used with tri-*i*-propyl and tri-*t*-butyl phosphates, traced a curved line of decreasing negative slope as the value of time increased. Thus, the reaction order was greater than one.

The rate of disappearance of the ester in a second order reaction* is given by the differential equation

$$-\frac{d[E]}{dt} = k[E][B],\ [E] \neq [B] \qquad \text{(Eq. 11)}$$

where [B] = concentration of base, [E] = concentration of ester. From the stoichiometry of the reaction

$$[E]_0 - [E] = [B]_0 - [B] \qquad \text{(Eq. 12)}$$

where $[E]_0$ = concentration of ester at t = 0 and $[B]_0$ = concentration of base at t = 0. Rearrangement of Eq. 12 gives

$$[B] = [B]_0 - [E]_0 + [E] \ . \qquad \text{(Eq. 13)}$$

Substitution of Eq. 13 into Eq. 11 and rearrangement gives

$$-\frac{d[E]}{[E][B] - [E]_0 + [E]} = kdt \qquad \text{(Eq. 14)}$$

---

* The stoichiometry is assumed to be one mole of ester per mole of base.

Integration of Eq. 14 using the method of partial fractions, rearrangement, and simplification yields

$$\frac{1}{[B]_o - [E]_o} \ln \frac{[E]_o [B]}{[E]_o [E]} = kt \qquad \text{(Eq. 15)}$$

Since

$$ml_A \times N_A = ml_B \times N_B \qquad \text{(Eq. 16)}$$

where ml_A = milliliters of standard HCl required, ml_B = aliquot sample volume,

N_A = normality of HCl soln.,

N_B = normality of base,

then

$$[B] = N_B = ml_A \times \frac{N_A}{ml_B} \qquad \text{(Eq. 17)}$$

Thus, the concentration of hydroxide is known at any time, t, from the milliliters of standard hydrochloric acid required. The concentration of ester at time t can be found by substitution of Eq. 17 into Eq. 12 and rearrangement.

$$[E] = [E]_o - [B]_o - ml_A \times \frac{N_A}{ml_B} \qquad \text{(Eq. 18)}$$

Plotting $\log \frac{[B]}{[E]}$ vs. t should give a straight line of slope $\frac{([B]_o - [E]_o]}{2.303} k$ if the reaction is second order. Plots of the collected data in this fashion show a good fit to a straight line. In one run the concentration

of ester and base were equal (see Table 13-3). In this case, the rate of disappearance of ester with time is given by the equation

$$-\frac{d[E]}{dt} = k[E]^2 \qquad \text{(Eq. 19)}$$

Rearrangement of Eq. 19 followed by integration gives

$$\left.\frac{1}{[E]}\right]_{E_o}^{E} = kt\Big]_{o}^{t} \qquad \text{(Eq. 20)}$$

Evaluating Eq. 20 gives

$$\frac{1}{[E]} - \frac{1}{[E_o]} = kt. \qquad \text{(Eq. 21)}$$

Since $[B] = [E]$, then substitution of Eq. 17 into Eq. 21 gives

$$\frac{ml_B}{N_A}\left(\frac{1}{ml} - \frac{1}{ml_o}\right) = kt.$$

Plotting $\frac{1}{ml}$ vs. t should give a straight line of slope $\frac{N_A}{ml_B}$ k. The collected data plotted in this manner show a good fit to a straight line. A least-squares fit of the data from each run was calculated and the rate constant obtained from the calculated least-squares slope.

Table 16 lists quantities used in preparing solutions for each run, the values of time, milliliters of standard acid required and the concentration function, log $[B]/[E]$ or $1/ml$. The last column lists comparison values of the concentration function calculated from the least-squares slope and intercept. Table 17 lists the initial concentration of ester and base, the measured rate constant, and the ionic strength

of solution.

Table 16. Solvolysis of Triallyl Phosphate in 50% Ethanol-water at 60°C.

1. 4 ml. of 1.000 N NaOH/100 ml. solvent.
5.6328 g. $NaClO_4$/100 ml. solution.
50 ml. of solution transferred to a polyethylene bottle.
0.3177 g. triallyl phosphate/50 ml. solution at 60°C.
4.0-ml. aliquots titrated with 0.0494 N HCl.

Time (hrs.)	ml.	Observed log [B]/[E]	Calculated log [B]/[E]
0.00	3.03	0.0866	0.084
1.00	3.00	0.0870	0.087
2.00	2.90	0.0908	0.091
3.28	2.83	0.0937	0.096
5.00	2.67	0.0990	0.101
6.00	2.48	0.1074	0.104

$k = 3.24 \times 10^{-4}$ lit/mole sec.

2. 8 ml. of 1.000 N NaOH/100 ml. solvent.
5.1430 g. $NaClO_4$/100 ml. solution.
50 ml. of solution transferred to a polyethylene bottle.
0.3490 g. triallyl phosphate/50 ml. solution at 60°C.
4.0-ml. aliquots titrated with 0.0494 N HCl.

Time (hrs.)	ml.	Observed log [B]/[E]	Calculated log [B]/[E]
0.00	6.20	0.379	0.382
1.00	6.01	0.399	0.399
2.00	5.85	0.418	0.416
3.00	5.70	0.436	0.432
5.00	5.50	0.464	0.466
6.00	5.39	0.481	0.483

$k = 2.61 \times 10^{-4}$ lit/mole sec.

3. 16. ml. of 1.000 N NaOH/100 ml. solvent.
4.1636 g. $NaClO_4$/100 ml. solution.
50 ml. of solution transferred to a polyethylene bottle.
1.6321 g. triallyl phosphate/50 ml. solution at 60°C.
4.0-ml. aliquots titrated with 0.0494 N HCl.

Time (hrs)	$ml._t$	Observed $1/ml._t$	Calculated $1/ml._t$
0.00	12.16	0.082	0.083
1.00	10.22	0.098	0.098
2.00	8.74	0.114	0.114
2.95	7.76	0.129	0.129
4.97	6.16	0.1627	0.160
5.95	5.67	0.176	0.175
6.97	5.25	0.190	0.191
8.27	4.76	0.210	0.211

$k = 3.49 \times 10^{-4}$ lit/mole sec.

4. 20 ml. of 1.000 N NaOH/100 ml. solvent.
3.6737 g. $NaClO_4$/100 ml. solution.
50 ml. of solution transferred to a polyethylene bottle.
1.6712 g. triallyl phosphate/50 ml. solution at 60°C.
4.0-ml. aliquots titrated with 0.0494 N HCl.

Time (hrs.)	ml.	Observed log [B]/[E]	Calculated log [B]/[E]
0.00	15.36	0.093	0.096
1.00	12.83	0.114	0.115
2.00	11.00	0.136	0.134
2.93	9.92	0.153	0.151
4.97	8.20	0.194	0.190
5.93	7.79	0.207	0.208
6.97	7.29	0.226	0.228
7.93	6.83	0.246	0.246

$k = 3.32 \times 10^{-4}$ lit/mole sec.

Table 17. Rate Constants for the Solvolysis of Triallyl Phosphate in 50% Ethanol-water at 60°C.

Conc. Ester	Conc. Base	k x 10^4 lit/mole sec.	μ
0.0307	0.0374	3.24	0.497
0.0320	0.0766	2.61	0.497
0.1496	0.1502	3.49	0.490
0.1532	0.1897	3.32	0.490

Solvolysis of Tri-t-butyl Phosphate in H_2O^{18}-Ethanol

Cyclohexylamine (0.8156 g.) was weighed into a 50-ml. volumetric flask. Tri-t-butyl phosphate (2.0069 g.) was added and the flask was filled to the mark with a solvent prepared by mixing 25 ml. of D_2O enriched in O^{18} to 1.51 atom per cent (YEDA Research and Development Co., Ltd., Rehovoth, Israel) and 25 ml. of absolute ethanol.

The contents of the volumetric flask were transferred to a polyethylene bottle and the bottle placed in a 60° temperature bath. The reaction was allowed to proceed for a week. After this time, the contents of the bottle were emptied into a round-bottomed flask and the solvent removed under vacuum. The distillate was collected in a Dry Ice-acetone bath. When the distillation was completed, the solid remaining in the distilling flask was dried under vacuum for approximately 12 hours. The weight of solid was 2.2870 g. After two recrystallizations from 1,2-dimethoxyethane, the melting point of the cyclohexylammonium tri-t-butyl phosphate was 186.4-187.4° (decomp.).

A small quantity of this salt was mixed with mercuric chloride

and mercuric cyanide in a small break-seal tube. The break-seal tube was sealed under vacuum and then placed in a 500°C oven to pyrolyze the salt to carbon dioxide.* Analysis of the carbon dioxide on Consolidated-Nier Model 21-103 C mass spectrometer revealed a peak of mass 44 ($C^{12}O_2^{16}$) with a relative intensity of 6570 and a peak of mass 46 ($C^{12}O^{16}O^{18}$) with a relative intensity of 26. The percentage of O^{18} in the CO_2 can be calculated by the formula

$$\frac{H_1}{2(H_1 + H_2)} \times 100 = \% \, O^{18}$$

where H_1 is the intensity of $C^{12}O^{16}O^{18}$ and H_2 = intensity of $C^{12}O_2^{16}$. Substituting the quantities found into this equation gives 0.197% O^{18}, the natural abundance of O^{18}.

Collection and Reduction of X-ray Crystallographic Data

Crystals of methyl pinacol phosphate were grown from high-boiling petroleum ether (b.p. 90-120°). The ester was added in small quantities to a hot solution of petroleum ether until a saturated solution was obtained. Upon slow cooling of the solution, methyl pinacol phosphate crystallized in thin, flat plates (approximately 3 mm. x 0.5 mm. x 0.1 mm.). The melting point was 100-101°C. Occasionally, the material obtained in this recrystallization was pinacol phosphoric acid (m.p. 191°C, decomp.)

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* This procedure, a modification of that of Rittenberg and Porticarvo[56] is described in detail by Haake.[57]

56 D. Rittenberg and L. Ponticorvo, Int. J. Appl. Rad. and Isotopes, 1, 208 (1956).

57 P. C. Haake, Ph.D. Thesis, Harvard University, 1960.

which appears to have a much lower solubility in petroleum ether than the methyl ester. The acid will be preferentially deposited if the ester contains substantial amounts of the acid. Crystals of pinacol phosphoric acid obtained in this manner are long needles (approximately 3 mm. x 0.2 mm. x 0.2 mm.).

A crystal of the ester obtained by recrystallization was selected and mounted inside a 0.5 mm. capillary which was mounted on a standard goniometer head and affixed on a Buerger precession camera. After alignment of the crystal, with the b axis parallel to the spindle axis, Mo K (α) X-radiation was employed to obtain the diffraction data from the xkl and hkx layers, where x = 0-3.[58] Two crystals were required to collect all levels because of decomposition of the first crystal. Angles between the principal axes were 90° and mm symmetry was observed on all levels; these observations established the crystal system as orthorhombic. The systematic zero level extinctions, h 0 0, h = 2n + 1; 0 k 0, k = 2n + 1; 0 0 l, l = 2n + 1, indicated the space group $P2_12_12_1$. Reciprocal cell dimensions were a = 4.50 mm., b = 3.21 mm., and c = 5.54 mm. Direct cell dimensions were calculated by the formulas $a = \lambda \times d/a^*$, $b = \lambda \times d/b^*$, $c = \lambda \times d/c^*$ where a, b, c = direct cell dimensions in Å, λ = wave length of Mo K (α) = 0.711 Å, d = crystal to film distance = 60 mm, a^*, b^*, c^* = reciprocal cell dimensions in mm. The direct cell

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[58] For a complete discussion of X-ray diffraction camera techniques see M. J. Buerger, "X-ray Crystallography," John Wiley and Sons, Inc., New York, N. Y. (1942). A discussion of the precession camera technique can be found in M. J. Buerger, "The Precession Method, "John Wiley and Sons, Inc., New York, N. Y. (1964).

dimensions so calculated were a = 9.48 ± 0.01 Å, b = 13.24 ± 0.00 Å, and c = 7.70 ± 0.01 Å.

The intensities were estimated visually using a standard intensity series prepared from the crystal. Reflections on each of the three exposures were estimated and corrected for Lorentz and polarization effects.[59] A Patterson synthesis[60,61] was calculated; no consistent phosphorus positions were identified. Use of a minimum function[62,63] with approximately consistent phosphorus positions revealed little structure around the phosphorus. After many trials of various phosphorus positions, these data were abandoned, a new crystal mounted, and new data collected.

A crystal of methyl pinacol phosphate grown by slow sublimation was mounted inside a 0.5 mm. capillary. Crystals of the ester obtained by sublimation were approximately 2 mm. x 0.5 mm. x 0.5 mm. The faces of the crystal were the diagonal 101 planes. Unit cell dimensions for this crystal were the same as those found for the crystal obtained by recrystallization. Three intensity exposures of 12.0, 2.4, and 0.48 hours duration were recorded on a precession camera for each of the

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[59] A Lorentz-polarization correction program written for the Burroughs B5500 computer by Dr. J. A. Bertrand, was employed.

[60] See M. J. Buerger, "Crystal-Structure Analysis," John Wiley and Sons, Inc., New York, N. Y. (1960).

[61] A Fourier program written for the Burroughs B5500 computer by Dr. J. A. Bertrand was employed.

[62] See M. J. Buerger, "Vector Space," John Wiley and Sons, Inc., New York, N. Y. (1959).

[63] A minimum function program written for the Burroughs B5500 computer by Dr. J. A. Bertrand was employed.

levels h k x (x = 0-3), x k l (x = 0-3), h k h, (2 l)k l and h k (2 h). Mo K (α) radiation was employed. Table 18 lists pertinent camera settings for each of the eleven levels of data collected. Reproductions of the 12.0-hr. exposures are shown in Figs. 26 to 36.

Table 18. Camera Settings for Collection of X-ray Data on Methyl Pinacol Phosphate.

Zone	Spindle °	Screen Radius mm	Screen Distance mm	Film Distance mm	$\bar{\mu}$ °
h k 0	174° 30'	20	35.0	0.0	30
h k 1	174° 30'	25	30.0	5.5	30
h k 2	174° 30'	30	28.0	11.1	30
h k 3	174° 30'	30	27.0	16.6	20
0 k $\bar{1}$	84° 30'	20	35.0	0.0	30
1 k $\bar{1}$	84° 30'	25	32.0	4.5	30
2 k $\bar{1}$	84° 30'	30	30.5	9.0	30
3 k $\bar{1}$	84° 30'	30	31.0	13.5	20
h k h	123° 40'	20	35.0	0.0	30
($\bar{2}$ 1) k $\bar{1}$	142° 55'	20	35.0	0.0	30
h k ($\bar{2}$ h)	106° 40'	20	35.0	0.0	30

Intensities on each exposure for each level were estimated visually employing a standard series of intensities prepared from the same crystal. The intensities were corrected for Lorentz-polarization effects,[59] and, in all, 729 unique non-zero reflections were obtained. No corrections for absorption errors were applied.

A Patterson synthesis[60,61] revealed a consistent set of vectors of high intensity. The fractional coordinates of the phosphorus atom

were then obtained from the vector lengths. A structure factor[60,64] based on these phosphorus coordinates gave an R value of 0.41. A minimum function[62,63] based on these coordinates revealed the positions of the four oxygen atoms around the phosphorus atom. Inclusion of these atoms in a structure factor calculation brought the R value to 0.31. An electron density map[61] was calculated, with phases of F_o based on these five atoms. In all, 567 reflections whose observed and calculated F values agreed with $\pm$ 50% were used. The remaining atoms were located from this map. The structure factor R based on all atoms fell to 0.13; varying the x, y, z coordinates and the isotropic temperature factors[60] for each atom lowered the R value to 0.11. Finally, varying anisotropic temperature factors[60] brought the final R value to 0.09. Table 19 lists the comparison of observed and calculated structure factors for each h k l. A difference map based on all the atoms with anisotropic temperature factors showed small peaks around the carbon atoms attached to the ring and around the methyl ester group. These peaks probably represented hydrogen atoms but a complete set of fifteen hydrogen atoms could not be located and the bond lengths and angles of the hydrogen atoms were anomolous. Inclusion of these positions in a structure factor calculation gave little improvement in R values (R = 0.08). The hydrogen atoms were excluded from further structure factor calculations.

The structure factors for all unobserved reflections were calculated, based on the structure parameters determined. All structure

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[64] A translation of the Busing, Martin, and Levy fortran ORFLS least-squares refinement program for use on the Burroughs B5500 was employed in the calculation of the structure factors.

TABLE 19. COMPARISON OF OBSERVED AND CALCULATED STRUCTURE FACTORS

H	K	L	FO	FC	H	K	L	FO	FC	H	K	L	FO	FC	H	K	L	FO	FC
0	0	2	162	174	0	13	5	10	7	1	13	4	16	19	3	1	7	20	18
0	0	4	44	39	0	13	7	8	3	1	14	1	11	9	3	1	8	30	28
0	0	6	19	12	0	14	5	13	13	1	15	2	11	13	3	1	9	16	16
0	1	2	24	14	0	14	6	12	6	2	0	3	76	80	3	2	4	45	39
0	1	3	38	32	0	15	2	16	10	2	0	4	23	24	3	2	6	44	49
0	1	4	24	22	1	0	2	94	91	2	0	5	54	57	3	2	7	14	10
0	1	5	31	30	1	0	3	60	66	2	0	6	29	32	3	3	4	82	80
0	1	6	23	24	1	0	4	59	62	2	0	7	30	29	3	3	5	25	23
0	1	7	29	30	1	0	5	16	13	2	1	3	37	38	3	3	6	41	46
0	1	8	14	8	1	0	6	38	38	2	1	4	45	47	3	3	7	43	42
0	2	1	170	184	1	0	7	10	5	2	1	5	11	8	3	3	8	22	22
0	2	2	171	143	1	0	8	21	22	2	1	6	16	15	3	4	4	61	61
0	2	3	6	1	1	1	2	73	61	2	1	7	17	17	3	4	6	19	16
0	2	5	19	18	1	1	3	26	32	2	2	3	39	41	3	5	4	42	47
0	2	6	25	26	1	1	5	18	18	2	2	4	29	28	3	5	5	60	55
0	2	7	13	16	1	1	6	27	29	2	2	5	37	41	3	5	6	24	25
0	2	8	10	5	1	1	7	28	29	2	2	6	29	33	3	5	7	42	40
0	3	2	93	87	1	2	2	41	33	2	2	7	20	21	3	5	9	32	29
0	3	3	49	46	1	2	3	14	13	2	2	8	15	13	3	6	4	51	48
0	3	4	23	23	1	2	4	49	46	2	3	3	86	78	3	6	5	26	31
0	3	5	51	50	1	2	5	16	16	2	3	4	34	31	3	6	6	20	20
0	3	6	20	12	1	2	6	26	26	2	3	5	19	18	3	6	7	21	22
0	3	7	9	8	1	2	7	28	28	2	3	6	9	18	3	7	1	15	15
0	3	8	20	20	1	3	1	106	97	2	3	7	20	20	3	7	4	28	16
0	3	9	10	10	1	3	3	96	85	2	4	2	42	40	3	7	5	45	48
0	4	3	74	77	1	3	4	36	35	2	4	3	50	59	3	7	6	29	24
0	4	4	57	57	1	3	5	17	16	2	4	4	30	33	3	7	7	27	25
0	4	5	56	54	1	3	6	32	36	2	4	5	25	25	3	8	4	65	66
0	4	6	9	15	1	4	2	7	17	2	4	6	38	41	3	8	5	28	30
0	4	7	32	30	1	4	3	22	24	2	4	8	19	18	3	8	6	26	19
0	5	3	53	51	1	4	4	28	35	2	5	1	11	4	3	9	4	68	60
0	5	4	37	28	1	4	5	35	34	2	5	3	54	53	3	9	6	31	25
0	5	5	15	12	1	4	6	30	32	2	5	4	24	21	3	10	4	21	25
0	5	6	43	37	1	4	7	30	32	2	5	6	14	17	3	10	5	15	14
0	5	8	10	8	1	4	9	11	15	2	5	8	20	22	3	10	6	27	27
0	6	3	70	60	1	5	3	17	19	2	6	3	26	35	3	11	4	26	21
0	6	4	17	13	1	5	4	53	53	2	6	4	24	23	3	11	6	16	13
0	6	5	25	19	1	5	5	25	28	2	6	5	41	44	3	12	4	16	20
0	6	6	9	7	1	5	6	19	22	2	6	6	18	18	3	12	5	22	25
0	7	3	33	24	1	5	7	15	15	2	6	7	11	14	3	12	6	16	22
0	7	4	38	30	1	6	3	22	14	2	7	3	53	51	3	13	0	15	3
0	7	5	28	20	1	6	4	28	34	2	7	4	21	24	3	13	1	15	22
0	7	6	27	19	1	6	5	28	32	2	7	5	30	28	2	0	0	46	30
0	7	8	22	19	1	6	6	17	16	2	7	6	21	22	4	0	0	93	82
0	7	9	13	12	1	6	7	15	16	2	8	1	9	13	6	0	0	102	94
0	8	1	8	3	1	7	3	28	27	2	8	4	22	31	8	0	0	36	38
0	8	3	34	25	1	7	4	54	62	2	8	5	42	44	2	1	0	72	89
0	8	4	24	18	1	7	5	10	10	2	9	4	29	32	4	1	0	77	78
0	8	5	18	16	1	7	6	20	22	2	9	5	24	27	5	1	0	63	63
0	8	7	10	6	1	8	3	28	36	2	10	1	14	12	6	1	0	22	24
0	9	4	9	12	1	8	4	32	34	2	10	4	22	21	8	1	0	38	39
0	9	5	31	23	1	8	5	10	12	2	10	5	11	5	10	1	0	24	23
0	9	6	10	8	1	8	6	23	25	2	11	4	25	21	12	1	0	21	22
0	9	7	14	12	1	8	7	15	15	2	11	5	16	20	0	2	0	60	89
0	9	8	19	14	1	9	4	10	13	2	13	5	12	16	1	2	0	150	150
0	9	9	14	11	1	9	5	21	22	3	0	4	19	16	2	2	0	139	145
0	10	4	9	7	1	9	6	11	15	3	0	5	43	41	3	2	0	8	1
0	11	4	23	18	1	10	4	18	22	3	0	7	37	32	4	2	0	41	39
0	11	7	19	16	1	12	4	11	15	3	1	4	106	97	5	2	0	20	17
0	12	4	19	15	1	12	6	11	13	3	1	5	21	19	6	2	0	50	49
0	13	4	14	16	1	12	8	11	11	3	1	6	44	50	8	2	0	27	24

TABLE 19. (CONTINUED)

H	K	L	FO	FC	H	K	L	FO	FC	H	K	L	FO	FC	H	K	L	FO	FC
9	2	0	17	17	2	9	0	48	49	4	2	1	51	64	11	8	1	12	11
10	2	0	26	25	3	9	0	23	28	5	2	1	29	34	0	9	1	9	8
1	3	0	88	100	4	9	0	60	55	6	2	1	34	33	1	9	1	67	74
2	3	0	40	34	5	9	0	9	11	7	2	1	23	27	2	9	1	19	24
3	3	0	68	52	6	9	0	35	39	9	2	1	18	17	3	9	1	32	41
4	3	0	75	76	10	9	0	19	17	11	2	1	28	26	4	9	1	44	43
6	3	0	32	30	0	10	0	57	42	0	3	1	34	30	5	9	1	35	47
7	3	0	15	12	1	10	0	9	15	2	3	1	42	38	6	9	1	15	14
9	3	0	21	21	2	10	0	29	37	3	3	1	25	19	7	9	1	30	28
10	3	0	17	19	3	10	0	16	12	4	3	1	44	37	9	9	1	28	30
11	3	0	10	11	4	10	0	25	20	5	3	1	20	23	1	10	1	28	35
12	3	0	13	10	6	10	0	29	25	6	3	1	24	28	2	10	1	14	13
0	4	0	33	28	8	10	0	28	26	7	3	1	42	51	3	10	1	41	36
1	4	0	38	26	10	10	0	25	23	8	3	1	43	43	4	10	1	27	28
2	4	0	45	35	2	11	0	46	52	9	3	1	10	14	5	10	1	47	54
3	4	0	100	80	3	11	0	19	17	12	3	1	20	21	11	10	1	20	17
4	4	0	72	71	4	11	0	64	54	0	4	1	173	134	0	11	1	31	33
7	4	0	23	17	5	11	0	14	7	1	4	1	40	49	1	11	1	42	45
8	4	0	51	49	6	11	0	10	19	2	4	1	76	89	2	11	1	23	28
9	4	0	19	13	7	11	0	10	6	3	4	1	57	63	3	11	1	15	21
11	4	0	17	17	9	11	0	16	14	4	4	1	55	66	4	11	1	24	24
1	5	0	37	39	0	12	0	43	33	5	4	1	24	26	5	11	1	11	17
2	5	0	43	40	1	12	0	23	23	6	4	1	39	40	7	11	1	25	22
3	5	0	32	32	2	12	0	23	34	7	4	1	18	22	8	11	1	16	16
4	5	0	24	30	3	12	0	14	7	8	4	1	20	19	9	11	1	20	19
7	5	0	36	33	5	12	0	10	12	9	4	1	18	19	0	12	1	19	24
8	5	0	9	9	6	12	0	19	17	1	5	1	47	49	1	12	1	22	30
9	5	0	26	29	8	12	0	26	22	3	5	1	32	36	2	12	1	29	31
10	5	0	10	7	1	13	0	27	31	4	5	1	25	18	3	12	1	49	46
11	5	0	10	8	2	13	0	26	28	5	5	1	53	55	5	12	1	29	32
0	6	0	120	119	4	13	0	27	19	6	5	1	38	47	9	12	1	16	19
1	6	0	15	3	6	13	0	10	16	7	5	1	13	20	0	13	1	25	21
2	6	0	41	43	7	13	0	13	16	8	5	1	17	16	1	13	1	16	15
3	6	0	23	33	8	13	0	9	13	10	5	1	11	13	2	13	1	31	33
4	6	0	59	61	0	14	0	17	19	12	5	1	12	19	4	13	1	16	17
5	6	0	25	34	2	14	0	10	16	0	6	1	22	18	6	13	1	16	15
6	6	0	9	7	3	14	0	19	19	1	6	1	34	42	7	13	1	20	13
7	6	0	50	53	5	14	0	19	16	2	6	1	23	23	2	14	1	20	20
8	6	0	16	16	7	14	0	12	9	3	6	1	23	15	3	14	1	16	9
9	6	0	10	12	2	15	0	10	0	4	6	1	50	45	4	14	1	11	10
11	6	0	17	12	3	15	0	16	16	5	6	1	31	32	8	14	1	20	17
1	7	0	21	20	4	15	0	9	6	7	6	1	26	26	2	15	1	11	11
3	7	0	16	17	2	16	0	16	11	8	6	1	41	44	4	15	1	23	22
4	7	0	8	11	3	16	0	20	22	10	6	1	11	16	2	16	1	20	19
5	7	0	19	15	5	16	0	20	17	0	7	1	31	32	4	0	2	13	21
6	7	0	53	58	2	17	0	17	14	1	7	1	55	56	5	0	2	21	24
7	7	0	39	35	4	17	0	21	21	2	7	1	28	33	6	0	2	75	79
8	7	0	19	17	3	0	1	166	146	4	7	1	57	52	7	0	2	48	43
9	7	0	10	15	4	0	1	52	56	6	7	1	19	24	8	0	2	32	34
10	7	0	10	6	5	0	1	45	46	7	7	1	29	28	3	1	2	86	82
0	8	0	78	65	7	0	1	17	15	8	7	1	11	14	4	1	2	50	55
1	8	0	20	12	8	0	1	27	27	9	7	1	22	24	5	1	2	42	43
2	8	0	56	69	11	0	1	16	17	10	7	1	16	13	6	1	2	47	50
3	8	0	50	40	3	1	1	34	31	1	8	1	29	38	7	1	2	33	37
4	8	0	9	14	5	1	1	32	38	3	8	1	39	34	8	1	2	25	25
5	8	0	40	45	6	1	1	21	22	4	8	1	35	31	9	1	2	15	15
6	8	0	32	30	7	1	1	62	63	5	8	1	36	43	10	1	2	27	23
7	8	0	13	11	8	1	1	16	12	6	8	1	33	35	12	1	2	18	17
8	8	0	32	30	9	1	1	30	31	7	8	1	21	24	3	2	2	35	39
10	8	0	17	15	12	1	1	12	6	8	8	1	11	14	4	2	2	14	17

TABLE 19. (CONTINUED)

H	K	L	FO	FC	H	K	L	FO	FC	H	K	L	FO	FC	H	K	L	FO	FC
6	2	2	35	34	5	10	2	11	18	2	8	3	39	43	3	3	3	19	16
7	2	2	30	29	6	10	2	16	14	3	8	3	45	42	4	3	4	33	33
8	2	2	36	38	8	10	2	21	20	4	8	3	56	51	5	3	5	18	16
9	2	2	10	9	10	10	2	25	21	5	8	3	26	27	3	4	3	63	66
10	2	2	11	9	0	11	2	31	32	6	8	3	20	24	4	4	4	38	36
3	3	2	69	71	1	11	2	22	27	7	8	3	15	12	5	4	5	18	21
4	3	2	73	75	2	11	2	36	42	8	8	3	27	27	7	4	7	17	16
5	3	2	48	45	3	11	2	31	30	10	8	3	17	19	3	5	3	58	36
7	3	2	24	18	4	11	2	32	26	0	9	3	24	12	4	5	4	15	16
9	3	2	28	27	6	11	2	20	24	1	9	3	76	71	5	5	5	13	15
10	3	2	11	13	0	12	2	30	25	2	9	3	72	82	7	5	7	14	12
11	3	2	12	13	1	12	2	34	31	3	9	3	37	35	4	6	4	18	11
3	4	2	55	44	2	12	2	11	20	4	9	3	29	29	5	6	5	13	10
4	4	2	42	35	3	12	2	12	15	5	9	3	37	43	6	6	6	17	16
5	4	2	24	30	5	12	2	12	12	6	9	3	26	23	7	6	7	17	13
7	4	2	19	17	8	12	2	22	21	7	9	3	27	24	4	7	4	20	18
10	4	2	11	8	0	13	2	17	18	9	9	3	23	19	5	7	5	17	18
0	5	2	24	19	1	13	2	27	29	10	9	3	17	17	6	7	6	20	18
1	5	2	91	83	2	13	2	12	17	0	10	3	21	27	7	7	7	13	9
2	5	2	58	52	4	13	2	24	18	1	10	3	18	20	4	8	4	19	19
3	5	2	14	13	3	14	2	12	13	2	10	3	37	36	5	8	5	17	17
4	5	2	49	48	5	14	2	22	17	3	10	3	43	35	7	8	7	15	14
5	5	2	15	17	3	15	2	13	10	4	10	3	42	39	4	9	4	16	11
7	5	2	48	44	3	16	2	22	23	5	10	3	36	34	6	9	6	14	13
8	5	2	15	11	6	0	3	34	35	6	10	3	31	32	4	11	4	19	18
0	6	2	25	18	7	0	3	29	29	0	11	3	65	58	2	14	2	14	12
1	6	2	14	10	8	0	3	27	30	1	11	3	46	50	1	15	1	10	10
2	6	2	69	69	10	0	3	22	19	2	11	3	20	28	4	16	4	11	9
3	6	2	52	51	11	0	3	28	25	3	11	3	21	24	1	17	1	15	15
4	6	2	34	39	6	1	3	59	65	6	11	3	23	22	2	17	2	16	14
5	6	2	20	23	7	1	3	79	84	9	11	3	29	29	2	18	2	11	6
6	6	2	30	32	8	1	3	44	47	0	12	3	26	18	4	2	8	20	19
7	6	2	20	21	9	1	3	33	36	1	12	3	26	35	4	4	8	20	20
1	7	2	39	41	6	2	3	41	45	2	12	3	34	32	4	6	8	20	18
2	7	2	12	16	7	2	3	34	39	3	12	3	38	29	1	9	2	9	5
3	7	2	17	23	8	2	3	38	42	4	12	3	22	17	2	13	4	14	15
5	7	2	45	51	11	2	3	23	16	5	12	3	32	30	1	14	2	10	8
6	7	2	40	45	5	3	3	48	42	0	13	3	39	31	2	15	4	13	13
7	7	2	18	15	6	3	3	73	84	1	13	3	32	32	1	16	2	13	10
9	7	2	20	16	7	3	3	27	36	2	13	3	32	26	1	17	2	14	14
0	8	2	87	84	8	3	3	24	21	4	13	3	33	31	2	0	1	75	69
1	8	2	23	30	10	3	3	27	22	0	14	3	16	19	8	0	4	26	32
2	8	2	30	39	12	3	3	29	23	2	14	3	17	16	10	0	5	10	14
3	8	2	42	37	6	4	3	74	75	2	15	3	29	26	2	1	1	60	62
4	8	2	10	21	7	4	3	25	25	0	16	3	34	28	8	1	4	17	19
5	8	2	27	26	8	4	3	40	40	2	16	3	17	18	10	1	5	14	17
6	8	2	30	28	5	5	3	43	47	2	17	3	29	24	2	2	1	17	9
7	8	2	22	19	6	5	3	37	41	1	0	1	173	177	8	2	4	14	13
8	8	2	23	19	7	5	3	19	19	2	0	2	110	98	8	3	4	17	17
9	8	2	12	12	10	5	3	16	18	3	0	3	27	31	10	5	5	13	13
0	9	2	30	34	4	6	3	34	35	4	0	4	18	16	4	7	2	9	17
2	9	2	39	39	5	6	3	41	40	1	1	1	186	192	8	7	4	14	13
3	9	2	37	36	6	6	3	33	36	2	1	2	24	21	8	10	4	13	13
4	9	2	65	60	8	6	3	30	26	3	1	3	49	48	4	12	2	10	3
5	9	2	21	23	10	6	3	23	21	4	1	4	32	31	6	12	3	10	10
9	9	2	12	12	3	7	3	35	31	1	2	1	63	53	6	13	3	9	11
0	10	2	27	19	4	7	3	93	83	2	2	2	22	26	2	15	1	10	11
1	10	2	29	27	5	7	3	21	27	3	2	3	21	24	2	16	1	18	19
2	10	2	33	40	6	7	3	23	18	4	2	4	16	10					
3	10	2	15	13	7	7	3	32	22	5	2	5	25	26					
4	10	2	15	13	8	7	3	26	23	2	3	2	47	53					

factors for these reflections were below the maximum required for these values to be observable.

Agreement of these structure parameters with the first set of data was checked. A least-squares structure factor refinement using the first set of data showed insignificant changes in parameter values. The lowest R value obtained with the old data was 0.16.

Table 20 lists the x, y, and z parameters for each atom. The limit of error is given in parentheses beside the number and corresponds to the uncertainty in the last significant digit. Anisotropic temperature β values are given in Table 21 with the error in parentheses.

A crystal of pinacol phosphoric acid was also examined by X-ray diffraction. The crystal system was found to be orthorhombic as indicated by 90° angles between all axes. However, mm symmetry was not observed on upper levels. Furthermore, systematic extinctions did not correspond to any orthorhombic space group. Presumably, this is an example of a pseudo-orthorhombic system reported by Dunitz.[65] Unit cell dimensions found were a = 12.19 $\mathring{A}$, b = 10.66 $\mathring{A}$, and c = 7.11 $\mathring{A}$. Assuming a reasonable density in the range of 1.0-1.5 g./cm.^{3}, the number of molecules per unit cell is four. The calculated unit cell volume is 923.9 $\mathring{A}^3$.

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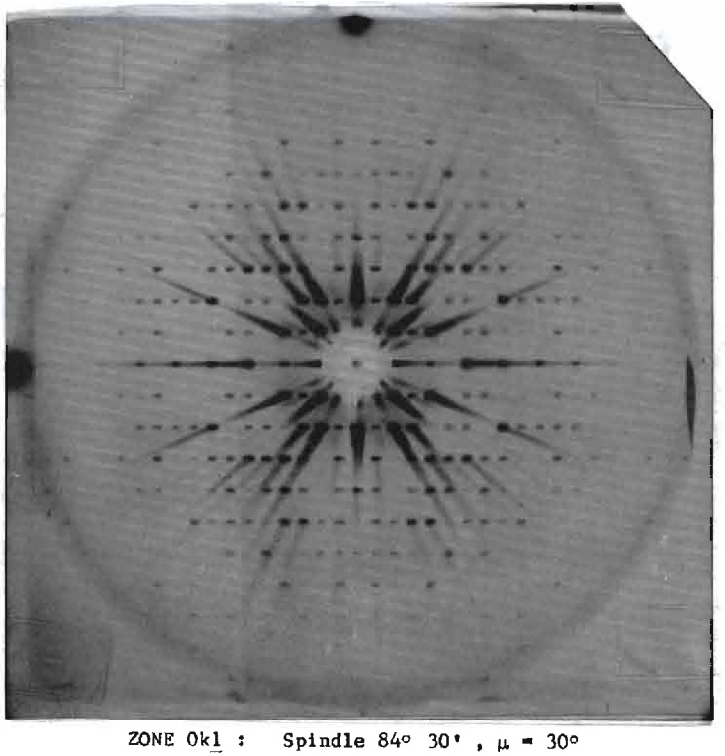
[65] J. D. Dunitz, Acta Cryst., 17, 1299 (1964).

Table 20. Final Atomic Parameters for Methyl Pinacol Phosphate.

Atom	x	y	z
P_1	0.1894(3)	0.2008(2)	0.2222(5)
O_2	0.102 (1)	0.1669(7)	0.385 (1)
O_3	0.131 (1)	0.1208(6)	0.088 (1)
O_4	0.3429(9)	0.1707(6)	0.2748(2)
O_5	0.180 (1)	0.3033(6)	0.163 (1)
C_6	-0.013 (2)	0.0963(9)	0.339 (2)
C_7	0.049 (1)	0.0386(8)	0.175 (2)
C_8	0.466 (1)	0.224 (1)	0.214 (2)
C_9	-0.141 (2)	0.162 (1)	0.292 (3)
C_{10}	-0.039 (2)	0.030 (1)	0.498 (2)
C_{11}	0.154 (1)	-0.0420(8)	0.228 (2)
C_{12}	-0.054 (2)	0.004 (1)	0.043 (2)

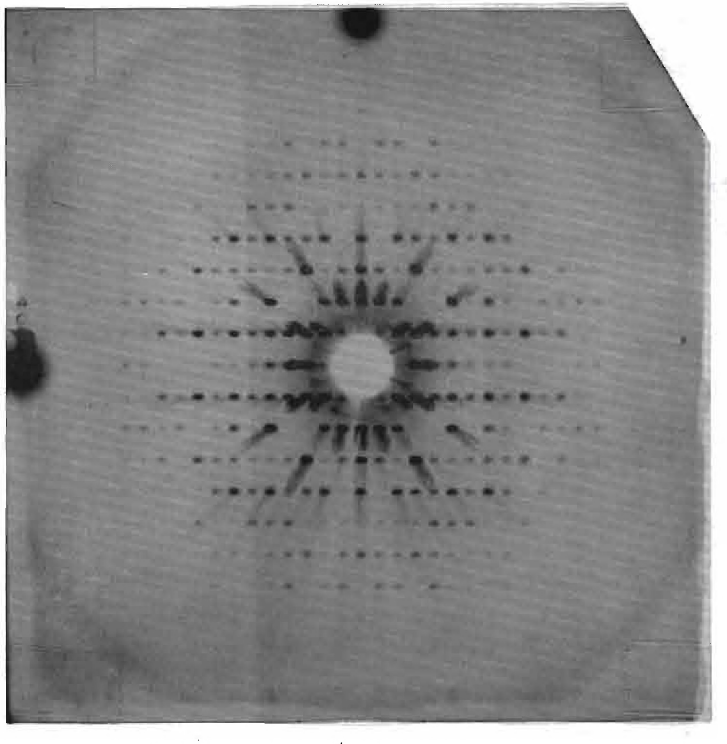
Table 21. Final Thermal Parameters for Methyl Pinacol Phosphate.

Atom	$\beta_{1,1}$	$\beta_{2,2}$	$\beta_{3,3}$	$\beta_{1,2}$	$\beta_{1,3}$	$\beta_{2,3}$
P_1	0.0073(3)	0.0032(2)	0.0141(8)	-0.0002(2)	0.0004(6)	0.0005(3)
O_2	0.011 (1)	0.0052(6)	0.013 (2)	-0.0029(8)	0.001 (2)	-0.003 (1)
O_3	0.009 (1)	0.0046(6)	0.011 (2)	-0.0006(7)	0.004 (2)	0.0002(9)
O_4	0.008 (1)	0.005 (6)	0.026 (3)	-0.0007(7)	-0.002 (2)	0.001 (1)
O_5	0.012 (1)	0.0039(5)	0.021 (2)	0.0012(9)	-0.001 (2)	0.000 (1)
C_6	0.012 (2)	0.0033(7)	0.015 (3)	0.000 (1)	0.003 (3)	-0.001 (1)
C_7	0.008 (2)	0.0032(6)	0.014 (3)	-0.0007(9)	0.001 (2)	-0.000 (1)
C_8	0.007 (1)	0.007 (1)	0.015 (4)	-0.000 (1)	-0.002 (2)	0.001 (2)
C_9	0.008 (2)	0.007 (1)	0.028 (5)	0.002 (1)	-0.003 (3)	-0.003 (2)
C_{10}	0.013 (2)	0.007 (1)	0.014 (3)	-0.003 (1)	0.007 (3)	0.001 (2)
C_{11}	0.012 (2)	0.0023(6)	0.027 (4)	0.0013(9)	0.005 (3)	0.000 (1)
C_{12}	0.013 (2)	0.0057(9)	0.016 (4)	-0.003 (1)	-0.004 (3)	-0.002 (2)



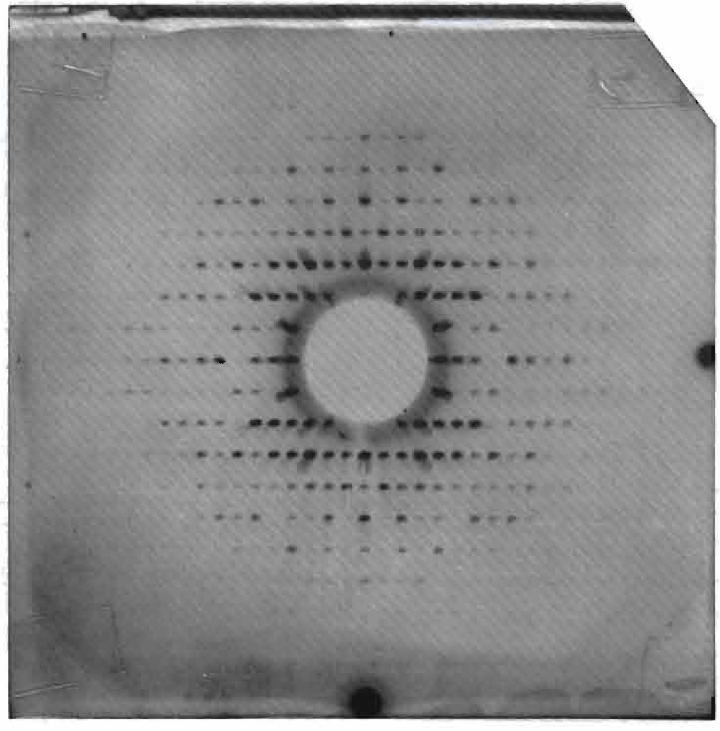
ZONE 0k$\underline{l}$: Spindle 84° 30' , μ = 30°

Fig. 26. X-ray Diffraction Data: Zone 0 k $\underline{l}$.



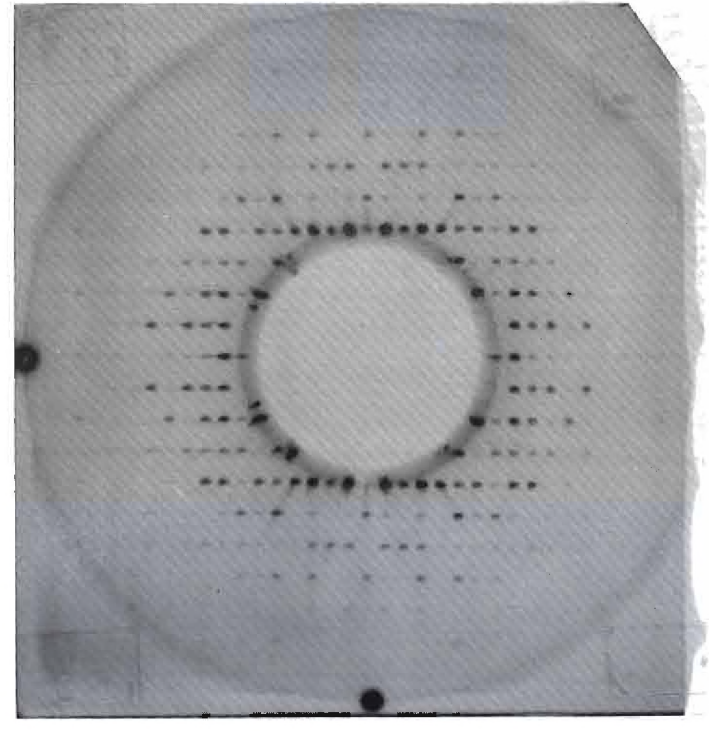
ZONE 1k$\underline{l}$: Spindle 84° 30' , μ = 30°

Fig. 27. X-ray Diffraction Data: Zone 1 k $\underline{l}$.



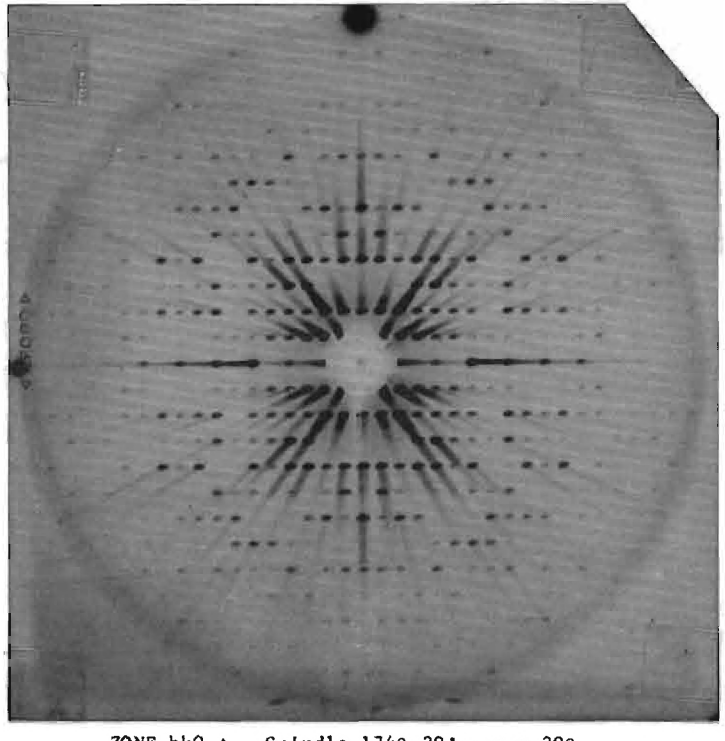
ZONE 2k1 : Spindle 84° 30' , μ = 30°

Fig. 28. X-ray Diffraction Data: Zone 2 k l.



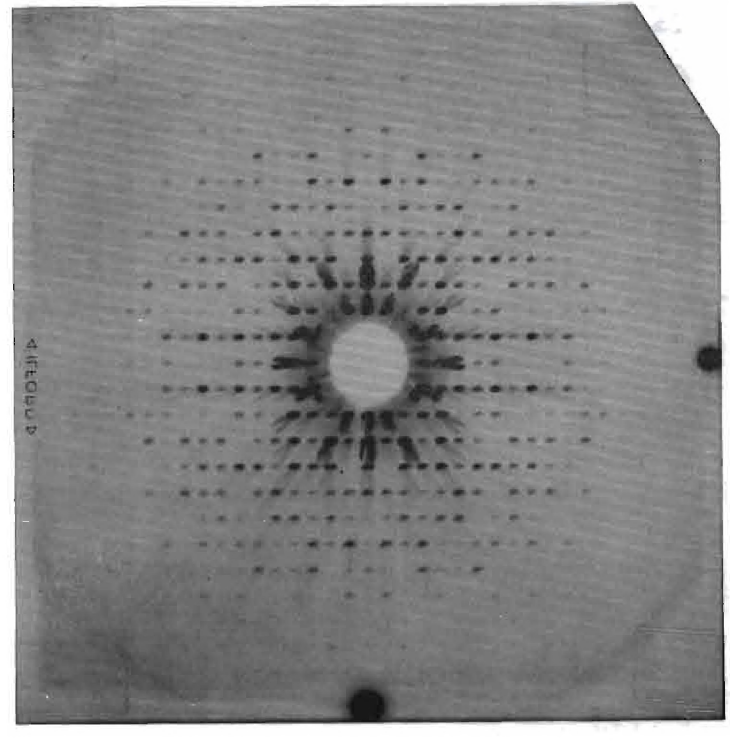
ZONE 3k1 : Spindle 84° 30' , μ = 20°

Fig. 29. X-ray Diffraction Data: Zone 3 k l.



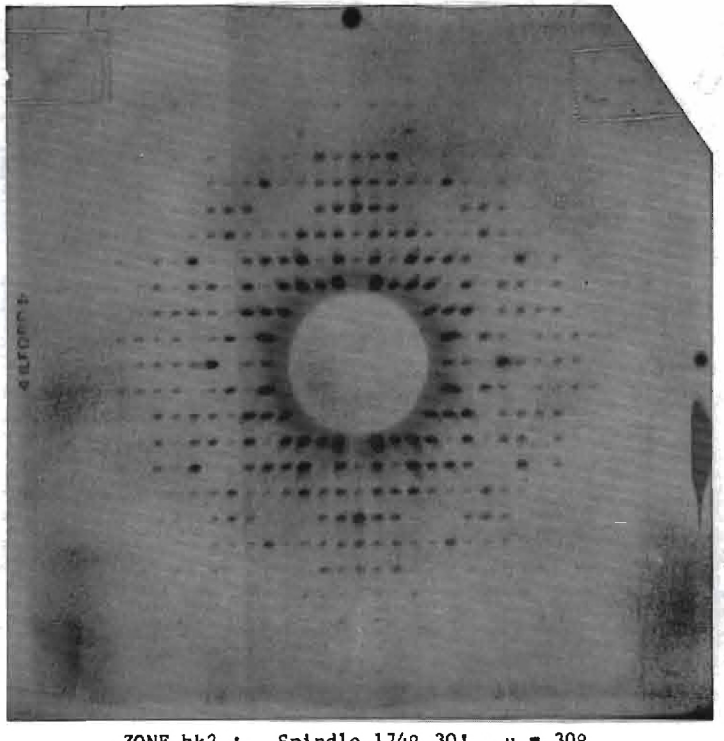
ZONE hk0 : Spindle 174° 30' , μ = 30°

Fig. 30. X-ray Diffraction Data: Zone h k 0.



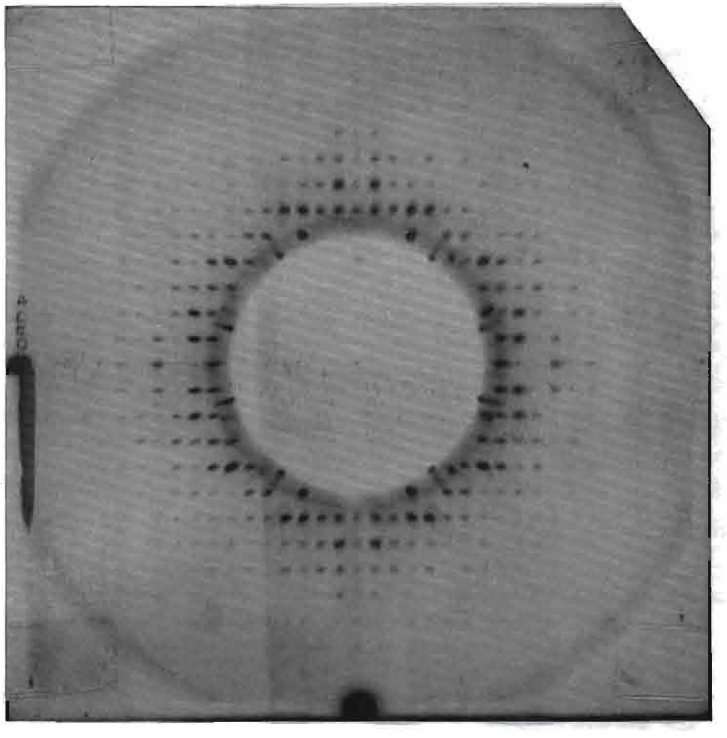
ZONE hk1 : Spindle 174° 30' , μ = 30°

Fig. 31. X-ray Diffraction Data: Zone h k 1.



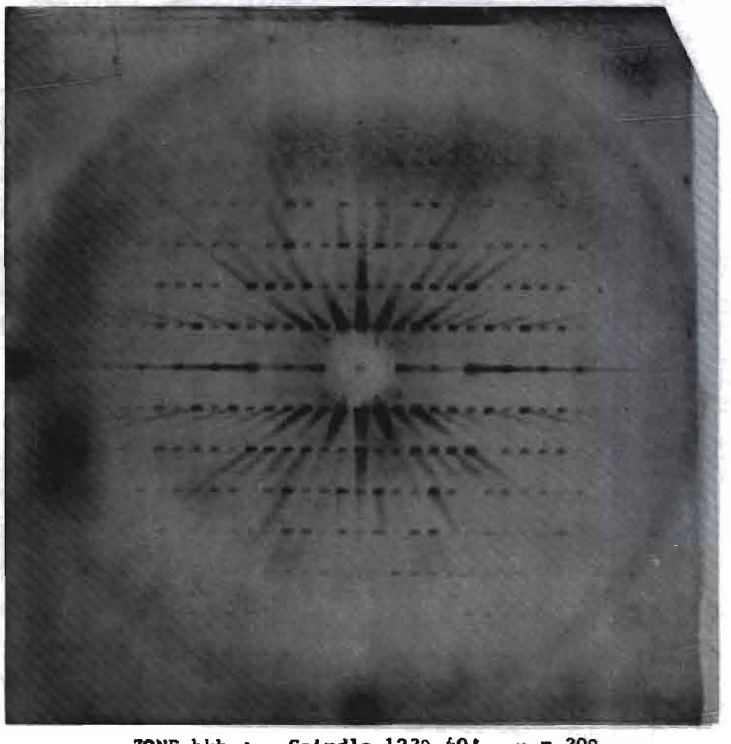
ZONE hk2 : Spindle 174° 30' , μ = 30°

Fig. 32. X-ray Diffraction Data: Zone h k 2.



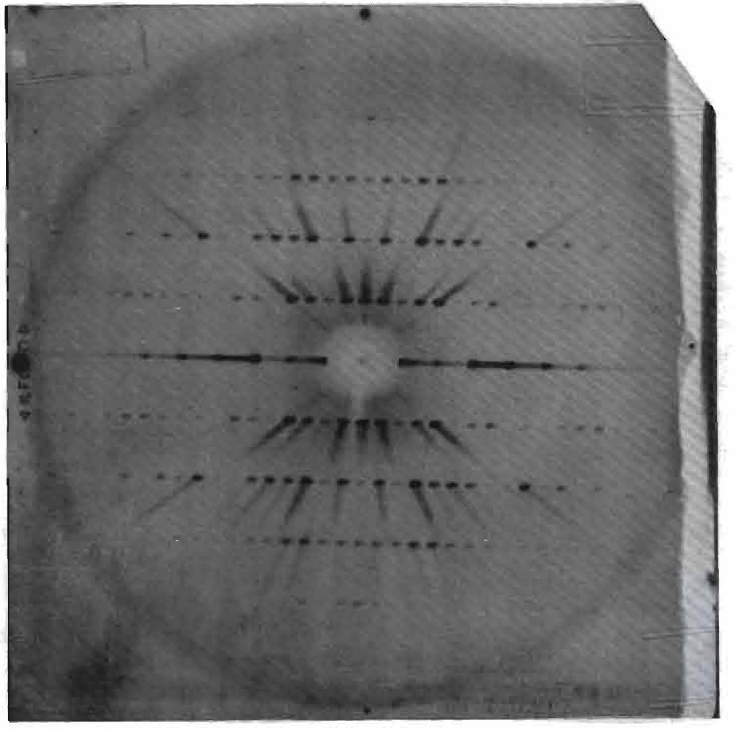
ZONE hk3 : Spindle 174° 30' , μ = 20°

Fig. 33. X-ray Diffraction Data: Zone h k 3.



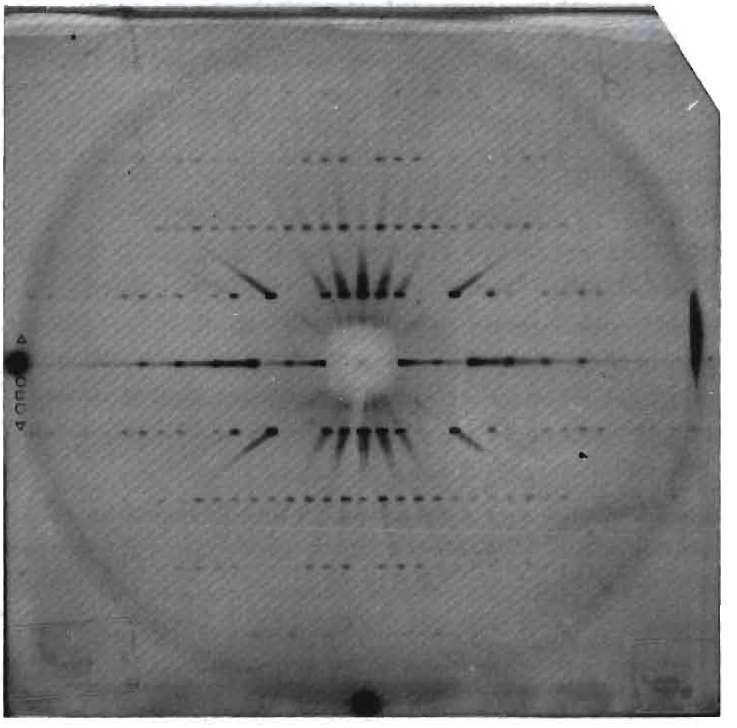
ZONE hkh : Spindle 123° 40' , μ = 30°

Fig. 34. X-ray Diffraction Data: Zone h k h.



ZONE (21)kl : Spindle 142° 55' , μ = 30°

Fig. 35. X-ray Diffraction Data: Zone (2 1) k l.



ZONE hk(2h) : Spindle 106° 40' , μ = 30°

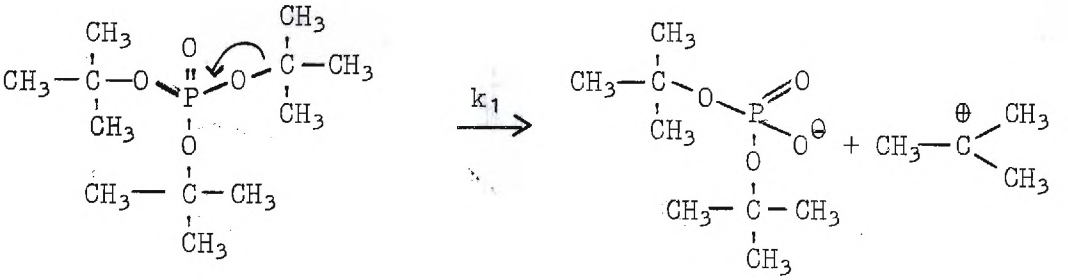
Fig. 36. X-ray Diffraction Data: Zone h k (2 h).

CHAPTER III

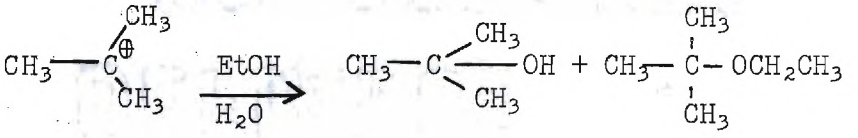
RESULTS AND DISCUSSION

Solvolysis of Tri-t-butyl Phosphate

From the kinetic results of Chapter II, tri-t-butyl phosphate hydrolyzes by a first-order mechanism over the entire solvent range and exhibits a large dependence on solvent polarity. The half-life of about three hours in 40% ethanol-water increases to a half-life of about 80 hours in 90% ethanol-water. The product of hydrolysis is di-t-butyl phosphate in nearly quantitative yield. From the results of the O^{18} exchange experiments, the bond which is broken in the hydrolysis is solely C-O, which leads to the conclusion that the mechanism of hydrolysis of tri-t-butyl phosphate proceeds by a rate-determining ionization to di-t-butyl phosphate monoanion and a t-butyl carbonium ion (Eq. 1). The carbonium reacts with solvent in a rapid second step to produce either t-butyl alcohol or ethyl t-butyl ether (Eq. 2).

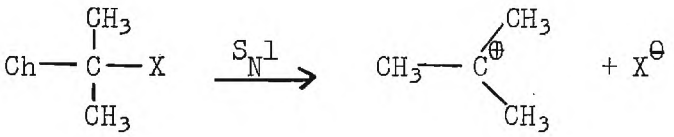


(Eq. 1)



(Eq. 2)

The mechanism of the hydrolysis of tri-t-butyl phosphate is equivalent to that of t-butyl halides,[66] i.e., in tri-t-butyl phosphate, the leaving group is the di-t-butyl phosphate anion, whereas in t-butyl chloride, the leaving group is the chloride anion (Eq. 3). The hydrolytic process of tri-t-butyl phosphate thus becomes an S_n1 displacement at carbon.



(Eq. 3)

A Grunwald-Winstein treatment[67] of the data of Table 13, Chapter II, results in a linear correspondence of the logarithm of the rate constant and the ionizing power of the solvent, Y. These data are plotted in Fig. 37. Although the deviation becomes quite large in the 40, 50, and 60% ethanol-water solvents, the large number of points determined in 50% ethanol-water probably compensates for the inaccuracy of single determinations. Also, the best straight line, calculated by a least-squares fit of the data, passes through the mid-point of the values in 50 and 60% ethanol-water and also nicely fits the points in the 70, 80, and 90% ethanol-water solvents. The spread of points in the more aqueous solvents is probably caused by a number of factors. An error in mixing the solvents in this range would result in greater error in the observed rate

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66 A. Streitwieser, Jr., "Solvolytic Displacement Reactions," McGraw-Hill Book Co., Inc., New York, N. Y. (1962), p. 38.

67 A. Streitwieser, Jr., ibid., p. 43; K. B. Wiberg, "Physical Organic Chemistry," John Wiley and Sons, Inc., New York, N. Y. (1964), p. 417; J. E. Leffler and E. Grunwald, "Rates and Equilibria of Organic Reactions," John Wiley and Sons, Inc., New York, N. Y. (1963), p. 297.

constants than an error in the less aqueous solvents. Furthermore, the addition of the ester (a relatively non-polar material compared to water) to the more aqueous solvents induces greater error in solvent polarity as compared to the less aqueous solvents.

The value of m, the slope of the line, was calculated from the data by a least-squares treatment. The magnitude of m obtained for tri-t-butyl phosphate was 0.467. This value lies intermediate to the observed m values of an S_N2 process (m = 0.25-0.35) and an S_N1 process (m = 1.0), but the mechanism of tri-t-butyl phosphate is clearly an S_N1 cleavage of the C-O bond. The low value of m obtained for tri-t-butyl phosphate indicates the relative effectiveness of di-t-butyl phosphate anion and chloride ion when functioning as leaving groups. The chloride ion is about twice as good a leaving group as di-t-butyl phosphate, neglecting temperature dependence of the Grunwald-Winstein relation.[68]

Solvolysis of Tri-i-propyl Phosphate

Tri-i-propyl phosphate is very inert toward hydrolysis in alkaline solution. Thus, in water at 60°C, the reaction in 0.1 N base is too slow to measure accurately. The data of Table 15, Chapter II, were recorded in water at 90°C, and even at this elevated temperature the compound hydrolyzes quite slowly. The data collected at this temperature show good first-order kinetics. However, the half-life (and consequently the rate coefficient) shows a dependency on the amount of ester present in solution. When the ester is present in very low concentrations (0.003 mole/liter), the half-life appears to approach a minimum of about 25 hours,

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[68] E. Grunwald and S. Winstein, J. Am. Chem. Soc., 70, 846 (1948).

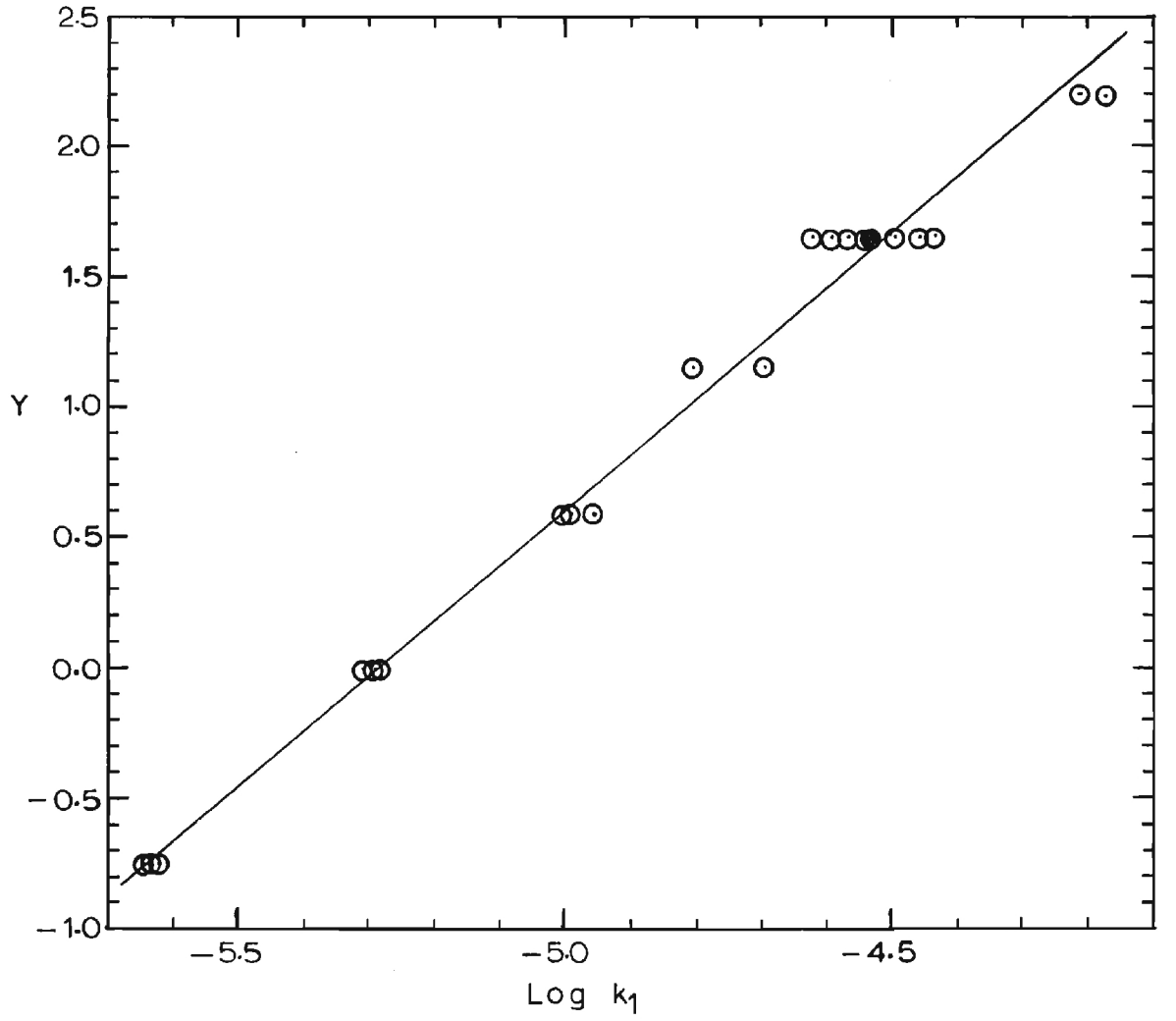
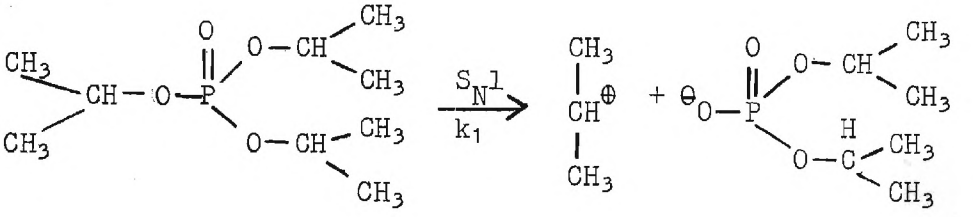


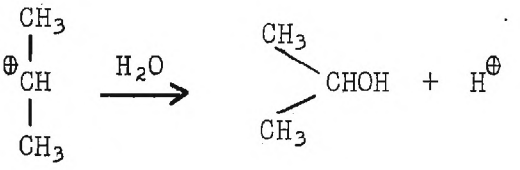
Fig. 37. Grunwald-Winstein Correlation of the Solvolysis Rates of Tri-t-butyl Phosphate.

which increases to about 70 hours when the concentration of ester is increased to ≈ 0.1 moles/liter. This effect is probably due to the change in polarity of the medium by the ester, inducing the lowest polarity of the medium when present in largest concentrations.

The bond-cleavage in the hydrolysis of tri-i-propyl phosphate was not determined by O^{18} labeling experiments, but the first-order kinetics indicate an S_N1 process (Eqs. 4,5), similar to tri-t-butyl phosphate. The ionization of an i-propyl cation is much less favorable than ionization of a t-butyl cation, thus the reaction has a large activation energy and is quite slow in comparison to tri-t-butyl phosphate.



(Eq. 4)



(Eq. 5)

Solvolysis of Triallyl Phosphate

The solvolysis of triallyl phosphate in basic solution in 50% ethanol-water at 60°C is second order, first order in hydroxide, and first order in ester. The position of bond-cleavage has not been determined.

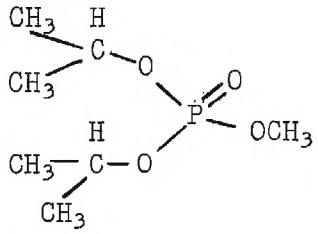
The Hydrolysis of the Pinacol Phosphate System

Attempts to measure the rate of alkaline hydrolysis of methyl

pinacol phosphate showed that hydrolysis was essentially complete within 60 seconds at 30°C. Assume that the reaction is first order in each reactant and that the concentrations of both reactants are approximately equal. The half-life for the reaction will be given by the relation

$$\frac{1}{a_0} = kt_{1/2}$$

where a_0 = initial concentration, $t_{1/2}$ = half-life, and k = rate constant. Suppose further, that within the period of 60 seconds, the reaction proceeded through a minimum of six half-lives. The maximum half-life would be approximately 10 seconds or, for the concentration of 0.1 molar, the rate constant would be at least 1.0 lit./mole sec. and probably much greater. A suitable acyclic compound, such as methyl di-i-propyl phosphate, I, with which the cyclic ester could be compared has not been studied. However, in light of the steric factors induced by branching at the α-

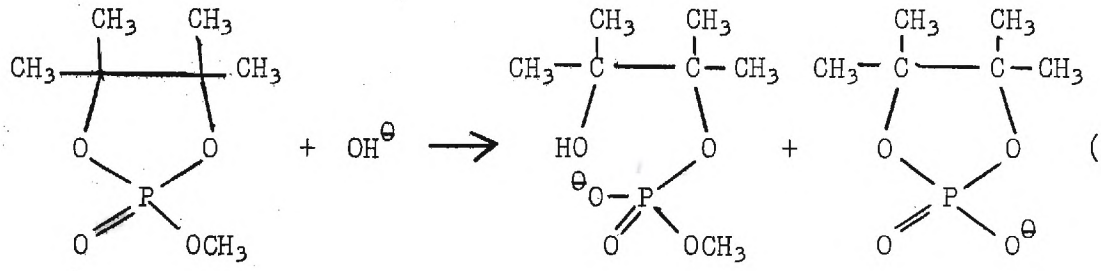


I

carbon atom, methyl di-i-propyl phosphate probably hydrolyzes in alkaline solution quite slowly with a rate constant in the range of 10^{-5} to 10^{-6} lit/mole sec. at 30°C. In view of these assumptions, methyl pinacol phosphate hydrolyzes at a greater ehhanced rate compared to simple non-cyclic triesters. A factor probably exceeding 10^5 is indicated but a

more quantitative estimate must await further experimentation. It is established, however, that the methyl pinacol phosphate system exhibits properties similar to other five-membered ring esters.

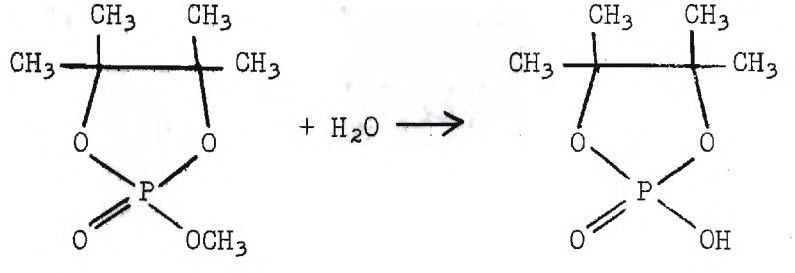
The product of hydrolysis of methyl pinacol phosphate in alkaline solution was a mixture of ring-opened (≈ 80%) and ring-retained (≈ 20%) diester salts (Eq. 6). However, small amounts of a ring-retained product



(Eq. 6)

were reported in the alkaline hydrolysis of methyl ethylene phosphate[69] and Fukoto and Metcalf[37] found predominant ring retention in the solvolysis of a series of p-nitrophenyl ethylene phosphates.

The behavior of methyl pinacol phosphate in initially neutral solution contrasted with that in alkaline solution. The only observed product of hydrolysis was pinacol phosphoric acid (Eq. 7) and the rate became



(Eq. 7)

measurable by conductrometric techniques. (The resistance decreased

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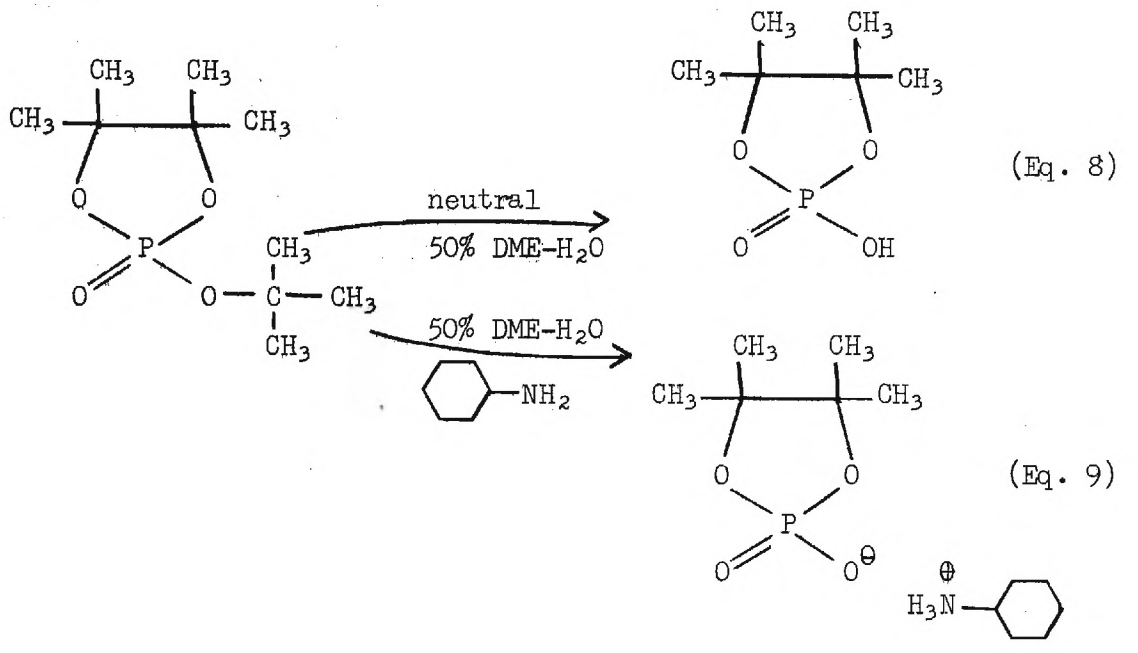
[69] F. Covitz and F. H. Westheimer, J. Am. Chem. Soc., 85, 1773 (1963).

steadily from 2260 ohms to 730 ohms in one hour for an initially 0.1 M solution of the ester in 50% dimethoxy-ethane-water.) The possibility that attack of hydroxide occurs at the methyl carbon is unlikely in view of the extremely slow reaction of water at carbon in trimethyl phosphate. However, when methyl ethylene phosphate is reacted with methanol, the ring opens to give dimethyl β-hydroxyethyl phosphate.[35]

The interesting triester, t-butyl pinacol phosphate, hydrolyzes in alkaline and neutral 50% 1,2-dimethoxyethane-water to give a ring-retained product (Eqs. 8, 9).



(Eq. 8)

(Eq. 9)

The X-ray Crystal Structure of Methyl Pinacol Phosphate

A view of the methyl pinacol phosphate molecule projected onto the XZ plane is displayed in Fig. 38. Tables 22 and 23 list the bond distances and angles of the structure, respectively, and comparison values of common bonds and angles of methyl ethylene phosphate[43] are also given. Standard

deviations of the least significant digit in distances and angles are given in parentheses. A packing diagram is shown in Fig. 39 viewed down the b axis.

Comparison of the common bond lengths in methyl ethylene and methyl pinacol phosphate shows that all bond distances are equivalent in the two structures except for an apparent lengthening of the ring C-C and C-O bonds. The angles O_2-C_6-C_7 and O_3-C_7-C_6 in methyl pinacol phosphate are smaller than the corresponding angles in methyl ethylene phosphate. The angles subtended by groups attached to the ring carbon atoms are somewhat distorted from the normal tetrahedral angle of 109.5°.

The dihedral angles between the O_2-P-O_3 plane and the O_2-C_6-O_3 and O_2-C_7-O_3 planes in methyl pinacol phosphate are 12.6 ± 1.0° and 11.8 ± 1.0°, respectively, as compared to 10.9° and 1.8° for the same planes in methyl ethylene phosphate. The angles demonstrate a greater puckering of the ring in the pinacol ester and this effect is readily seen in Fig. 40, which shows views of the methyl pinacol and methyl ethylene phosphate molecules looking along the ring C-C bond. Fig. 40 also indicates the steric repulsion of the pinacol ring methyl groups. The dihedral angles C_9-C_6-C_7-C_{12}, C_{10}-C_6-C_7-C_{11}, and O_2-C_6-C_7-O_3 are all approximately 35°, indicating greater strain in the pinacol system as compared to the ethylene system. Assuming that a normal dihedral angle would be about 60°, i.e., a staggered conformation, the excess strain energy can be estimated as approximately 1/3 of the rotation energy of the central C-C bond of pinacol.

The most significant difference in the two cyclic esters is the positioning of the methyl ester group. In methyl ethylene phosphate, the

methyl group occupies a position over the ring centered between the two-ring oxygen atoms; in methyl pinacol phosphate, the methyl group is rotated nearly 180° to a position over the phosphoryl oxygen. In both esters, the grouping O_5-P_2-O_4-C_8 is nearly planar. Although steric crowding requires that the methyl group not occupy a position over the ring, it is significant that the methyl ester group is turned through nearly 180°. This effect is shown in Fig. 41, in which the methyl ethylene and methyl pinacol phosphate structures are viewed down the phosphorus-methoxyl oxygen bond.

Although the effect could be explained as hydrogen bonding between phosphoryl oxygen and the methyl hydrogens,[70] the effect is more likely due to $d\pi$-$p\pi$ bonding between phosphorus and oxygen. The structures of triphenyl phosphate (a triester)[71] and dibenzyl phosphoric acid (a diester acid)[46] as well as a number of monophosphate derivatives[72] have been determined. A comparison of dibenzyl phosphoric acid, triphenyl phosphate, methyl ethylene phosphate, and methyl pinacol phosphate reveal the following common structural features:

1) Among the four P-O bonds, one bond is much shorter than the three remaining bonds.

2) Three of the P-O bonds are approximately equal in length.

3) A normal P-O-C bond angle appears to be 120°. This angle is

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[70] D. J. Sutor, J. Chem. Soc., 1105 (1963).

[71] W. O. Davies and E. Stanley, Acta Cryst., 15, 1092 (1962).

[72] E. Alver and S. Furberg, Acta Chem. Scand., 13, 910 (1959); K. N. Trueblood, P. Horn, and V. Tuzzati, Acta Cryst., 14, 965 (1961); J. Kraut, ibid., 14, 1146 (1961); E. Shefter and K. N. Trueblood, ibid., 18, 1067 (1965).

Table 22. Comparison of Bond Lengths in Methyl Pinacol Phosphate and Methyl Ethylene Phosphate.

Bond	Methyl Pinacol Phosphate	Methyl Ethylene Phosphate
P_1-O_2	1.57(1) Å	1.57(1) Å
P_1-O_3	1.59(1)	1.57(1)
P_1-O_4	1.56(1)	1.57(1)
P_1-O_5	1.44(1)	1.44(1)
O_2-C_6	1.49(2)	1.41(2)
O_3-C_7	1.50(1)	1.45(2)
O_4-C_8	1.44(1)	1.44(2)
C_6-C_7	1.59(2)	1.52(2)
C_6-C_9	1.53(2)	------
C_6-C_{10}	1.52(2)	------
C_7-C_{11}	1.51(2)	------
C_7-C_{12}	1.51(2)	------

Table 23. Comparison of Bond Angles in Methyl Pinacol Phosphate and Methyl Ethylene Phosphate.

Bonds	Methyl Pinacol Phosphate	Methyl Ethylene Phosphate
O_5-P-O_4	112.6(6)°	108.7(6)°
O_5-P-O_2	119.4(6)	116.0(6)
O_5-P-O_3	113.9(6)	117.3(6)
O_4-P-O_2	102.2(7)	105.7(6)
O_4-P-O_3	108.9(6)	109.2(6)
O_2-P-O_3	98.4(5)	99.1(6)
P-O_2-C_6	112.3(8)	112.0(9)
P-O_3-C_7	112.0(8)	112.0(9)
P-O_4-C_8	123.4(9)	118.8(9)
O_2-C_6-C_7	102 (1)	107.8(9)
C_6-C_7-O_3	101.4(9)	106.0(9)
O_2-C_6-C_9	106 (1)	-------
O_2-C_6-C_{10}	107 (1)	-------
O_3-C_7-C_{11}	107 (1)	-------
O_3-C_7-C_{12}	105 (1)	-------
C_7-C_6-C_9	112 (1)	-------
C_7-C_6-C_{10}	115 (1)	-------
C_6-C_7-C_{11}	112 (1)	-------
C_6-C_7-C_{12}	116 (1)	-------
C_9-C_6-C_{10}	113 (1)	-------
C_{11}-C_7-C_{12}	114 (1)	-------

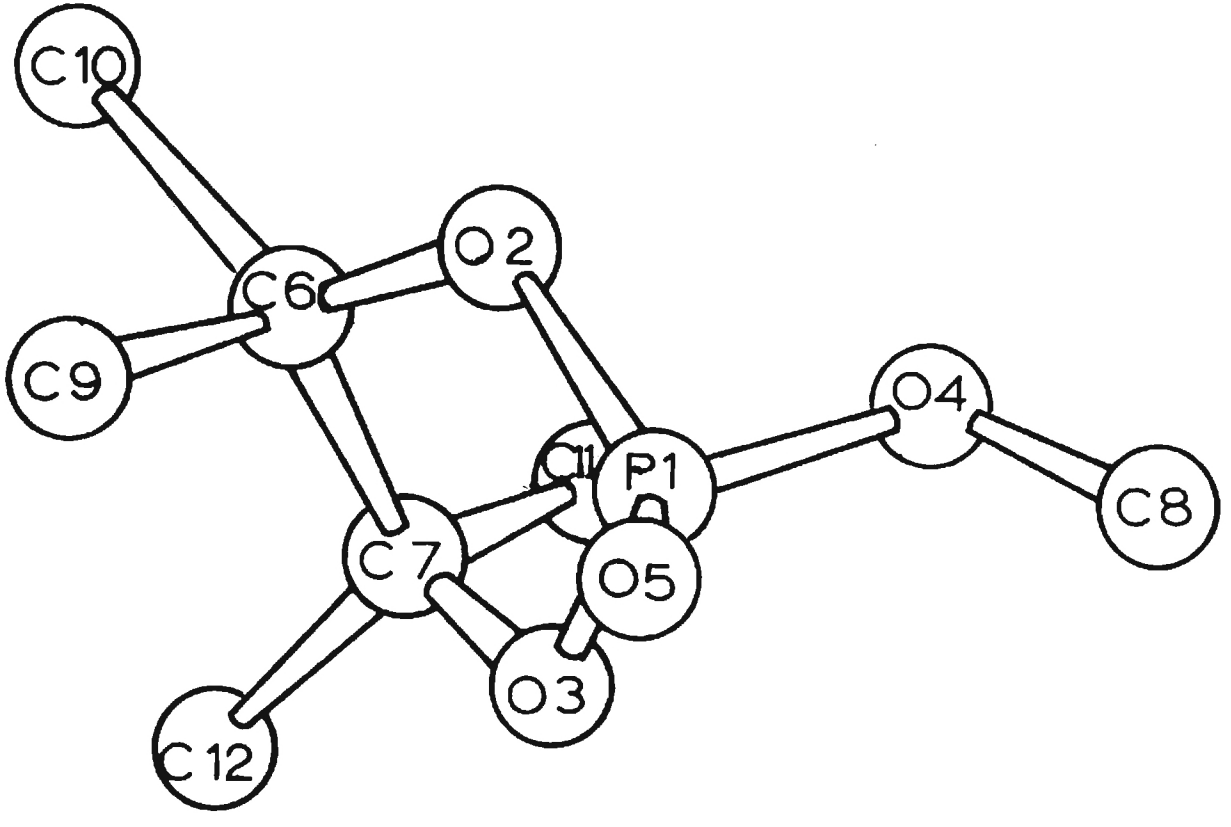


Fig. 38. Perspective drawing of one molecule of methyl pinacol phosphate as viewed down the y-axis.

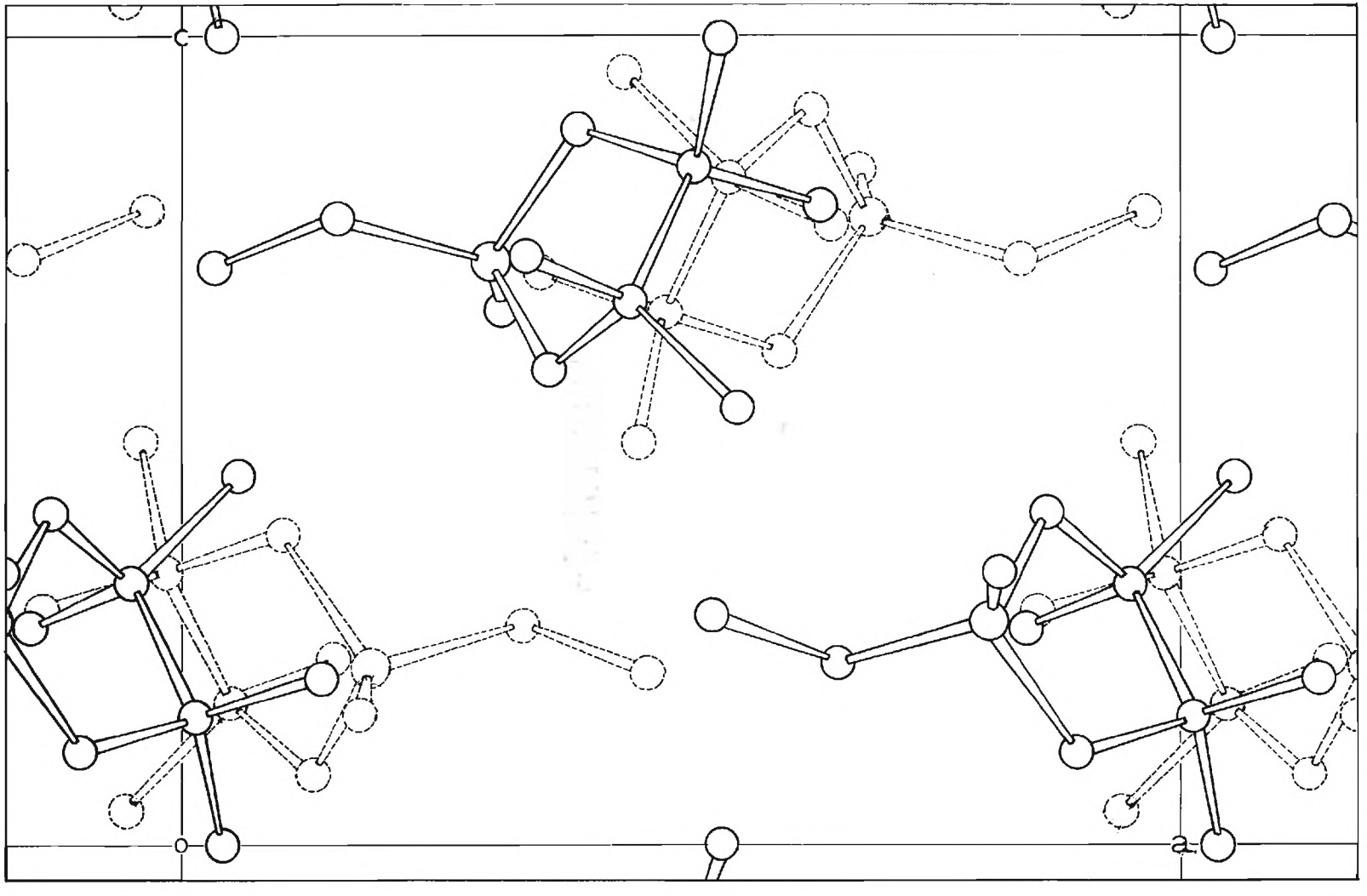


Fig. 39. A Lattice Packing Diagram of Methyl Pinacol Phosphate as Viewed Down the b-Axis.

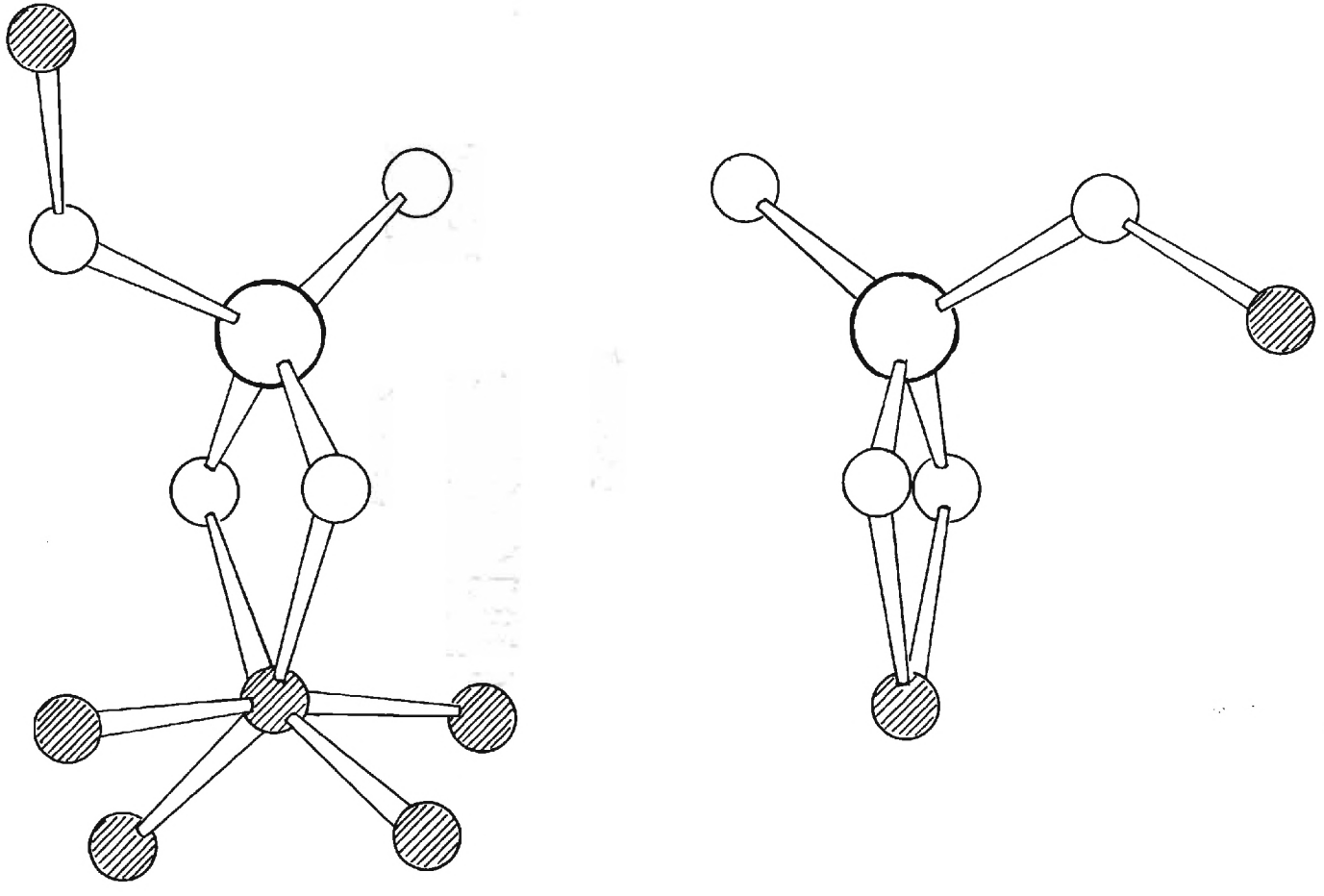
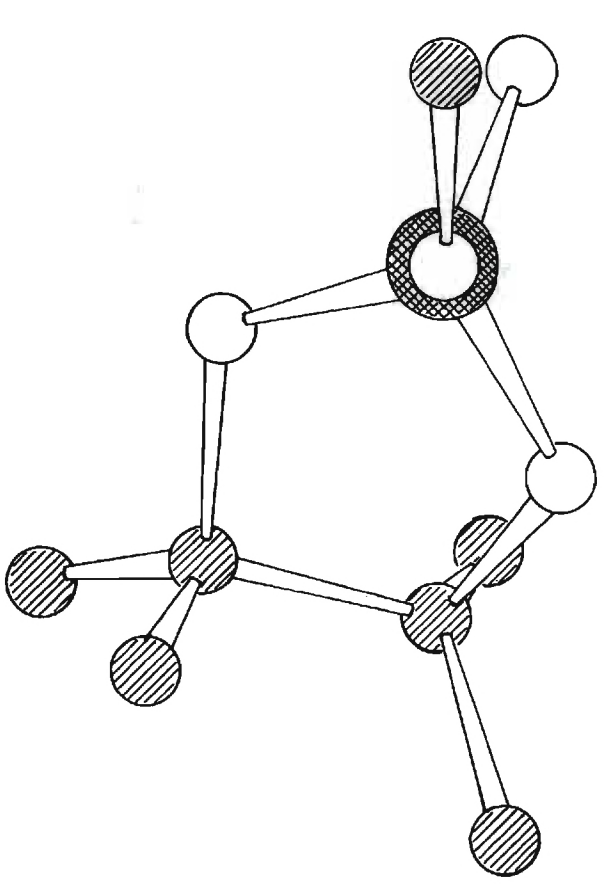
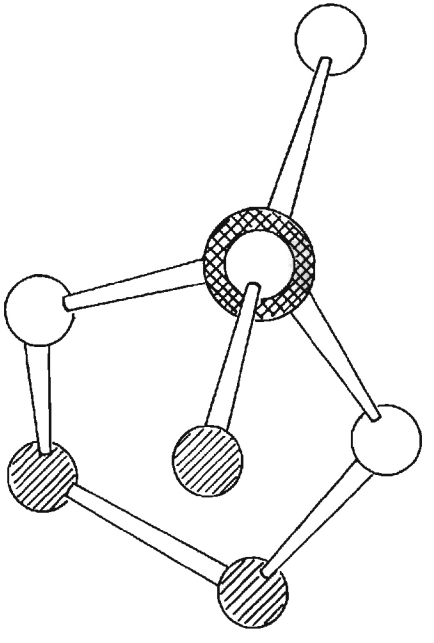


Fig. 40. Comparative Views of the Methyl Pinacol Phosphate and Methyl Ethylene Phosphate Molecules Viewed along the Ring Carbon-Carbon Bond.



METHYL PINACOL
PHOSPHATE



METHYL ETHYLENE
PHOSPHATE

Fig. 41. Comparitive Views of the Methyl Pinacol Phosphate and Methyl Ethylene Phosphate Molecules Viewed Along the Methoxyl Oxygen-Phosphorus Bond.

also observed for all monoesters reported. The angle is greatly constrained in five-membered ring esters.

4) One of the ester groups appears to be aligned in such a way that the four atoms, O'-P-O-C (O' = phosphoryl oxygen) are almost planar. The dihedral angle between the planes formed by O'-P-O and P-OC is 6.8^0 in dibenzyl phosphoric acid, 9.1^0 in triphenyl phosphate, 16.6^0 for methyl ethylene phosphate, and 20.7^0 for methyl pinacol phosphate.

Cruickshank[73] has discussed $d\pi$-$p\pi$ bonding in the phosphate group in terms of tetrahedral symmetry. Symmetry of this order is not realistic in view of the above experimental facts. Consequently, symmetry of lower order is considered for the bonding in the ester structures.

If C_{3v} symmetry is first assumed, the phosphorus d-orbitals give rise to an A_1 (d_{z^2}) and two E ($d_{x^2-y^2}$, d_{xy}, and d_{xz}, d_{yz}) representations (see Table 24 for irreducible representations for C_{3v}). Assuming that the

Table 24. Character Table for C_{3v} Symmetry Group.

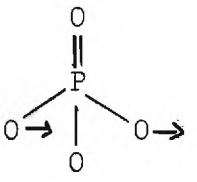
C_{3v}	E	2 C_3	3 σ_v
A_1	1	1	1
A_2	1	1	-1
E	2	-1	0

phosphoryl bond forms two π-bonds with D_{xz} and d_{yz},[18] a set of d orbitals

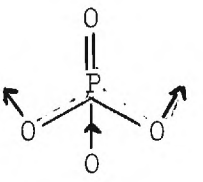
[73] D. W. J. Cruickshank, J. Chem. Soc., 5486 (1961).

with A_1 and E symmetry remain for π-bonding to the ester oxygen atoms. Since the normal POC bond angle is about 120°, the oxygen atoms may be considered as sp^2 hybrids, with a filled p-orbital perpendicular to its sp^2 plane.

If the three oxygen p-orbitals are aligned perpendicular to the C_{3v} mirror planes (Structure I), such a set of p-orbitals gives rise to



I



II

a representation reducible to E + A_2. No A_2 orbital is available on phosphorus and only two π-bonds can be formed. Rotation of the p-orbitals through 90° (Structure II) gives a set of p-orbitals reducible to E + A and three π-bonds are possible. Such an arrangement has not been found in any reported phosphate esters, and apparently indicates that the π-bonds of the ester oxygens and those of the phosphoryl group are not completely independent but interact to form molecular orbitals with greater delocalization.

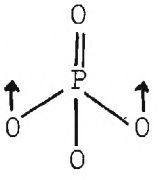
Consideration of lower symmetry, C_s, requires that only one p-orbital of oxygen remains perpendicular to the O'-P-O-C plane in agreement with experimental evidence. In C_s, the three available d-orbitals on phosphorus transform as A', A', and A". (A character table for C_s is shown in Table 25.) One arrangement of p-orbitals, in which one of the oxygen p-orbitals is aligned perpendicular to the symmetry plane and the two remaining oxygen atoms have p-orbitals parallel to the symmetry plane

Table 25. Character Table for C_s Symmetry Group.

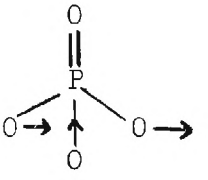
C_s	E	σ_h
A'	1	1
A"	1	-1

(Structure III), gives rise to a set reducible to A' + A" + A" and only two π-bonds are possible. Another arrangement (Structure IV), in which two p-orbitals on oxygen are perpendicular to the symmetry plane and the third is parallel to it, gives rise to a representation reducible to A' + A' + A" and three π-bonds are possible.

Since the arrangement shown in Structure IV allows three π-bonds



III



IV

to the set of three oxygen atoms and five π-bonds overall, it might be expected that this would be the normal arrangement. Triphenyl phosphate approaches this arrangement, with the π-bond planes (P-O-C plane) of two oxygen atoms approximately perpendicular (dihedral angles between O'-P-O and P-O-C are 93° and 172°); the dihedral angle between O'-P-O and P-O-C for the third oxygen is 154° and it therefore deviates from the expected 180°, but realistically, considerable involvement of all d-orbitals in

π-bonding is expected.

Significantly, methyl ethylene and methyl pinacol phosphate approach arrangement in Structure III. In methyl ethylene phosphate, the methyl ester group deviates only 16° from the O'-P-O plane and the π-orbital is perpendicular to this plane; the dihedral angles between the CH_3-O-P plane and the other two C-O-P planes are 84° and 89°. These considerations of symmetry indicate that π-bonding is reduced in five-membered esters since only two π-bonds are possible, although it is apparent that in the real system, much more interaction among the orbitals is occurring. Since one d-orbital is not involved in dπ-pπ bonding, the availability of this orbital should facilitate nucleophilic attack at phosphorus. This effect is offered in addition to ring strain to explain the reactivity of five-membered esters.

Collin[74] has advanced a different view of the interpretation of the X-ray results of phosphate ester structures. Using known structural parameters of phosphate esters and without imposing symmetry restrictions, the charge distribution and energies arising from dπ-pπ bonding were calculated employing a self-consistent molecular orbital approach. The difference in electronegativity between phosphorus and oxygen was considered in the calculation. The results of the calculation of charge distribution revealed that phosphorus in non-cyclic esters had less partial positive charge than phosphorus atoms in five-cyclic ring systems. The increased partial charge on phosphorus in five-membered rings was suggested to account for increased reactivity. Although formally different, both

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[74] R. L. Collin, private communication.

interpretations conclude that $d\pi$-$p\pi$ bonding is quite significant in phosphate esters, and a more complete understanding of this bonding is necessary for the interpretation of phosphate ester chemistry.

CHAPTER IV

CONCLUSIONS

The results presented in Cyapter III prove the mechanism of the basic solvolysis of tri-t-butyl phosphate in aqueous ethanol solvents to be preliminary ionization of the ester to di-t-butyl phosphate anion and a t-butyl carbonium ion. The ester solvolyses over the entire solvent range at a rate independent of the hydroxide ion concentration. The isotropic tracer study shows no incorporation of O^{18} in the phosphate fragment when the ester is solvolyzed in aqueous solvent containing H_2O^{18}. Furthermore, the logarithms of the rates of alkaline solvolysis for tri-t-butyl phosphate in 40,50,60,70,80, and 90% ethanol-water are linearly dependent on the Grunwald-Winstein Y values for these solvents. The value of m obtained from the slope of the linear graph is 0.467 $\pm$ 5%. This low value of the Grunwald-Winstein m (usually, for most S_N1 processes, m $\approx$ 1.0) apparently reflects the poorer leaving ability of di-t-butyl phosphate anion as compared to chloride ion, for example.

Although not proved by isotropic tracer studies, tri-i-propyl phosphate undergoes alkaline solvolysis by an ionization mechanism similar to that of tri-t-butyl phosphate. In water at 90°C., tri-i-propyl phosphate solvolyzes at a rate independent of the hydroxide ion concentration. Because of the greater amount of energy required to form the i-propyl cation compared to the t-butyl cation, the tri-i-propyl phosphate ester solvolyzes much more slowly than the tri-t-butyl ester, even at a higher temperature and in a more polar solvent.

Also apparent from these studies is the effect of steric hindrance imposed by three i-propyl residues attached to a phosphate nucleus. These groups shield the phosphorus atom so effectively that bimolecular nucleophilic attack at phosphorus is not competitive with the ionization process.

The solvolytic behavior in alkaline solution of the series of esters, trimethyl phosphate, triethyl phosphate, tri-i-propyl phosphate, and tri-t-butyl phosphate, is thus firmly established and is qualitatively similar to the behavior of the analogous alkyl halide series reported by Ingold.[75] Methyl and ethyl bromide solvolyze by bimolecular displacement of bromide ion by hydroxide ion from carbon; trimethyl and triethyl phosphate undergo solvolysis through bimolecular displacement of the alkoxide anion by hydroxide ion from phosphorus. t-Butyl bromide solvolyzes in alkaline solution by a first-order ionization process to form an intermediate t-butyl carbonium ion. This same mechanism was found for the solvolysis of tri-t-butyl phosphate. Both i-propyl bromide and tri-i-propyl phosphate solvolyze very slowly compared to the other members of the series. In the solvolysis of these compounds, bimolecular nucleophilic attack is hindered by steric interference of the attached groups; a large activation energy is associated with the alternative first-order ionization process. Thus, the i-propyl member of the series is quite resistant to solvolysis.

Triallyl phosphate solvolyzes at a rate dependent on both the hydroxide and ester concentrations and is therefore an example of bimolecular process. Three sites in the molecule are open to possible attack

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75 C. K. Ingold, "Structure and Mechanism in Organic Chemistry," Cornell University Press, Ithaca, N. Y. (1953), pp. 316-324.

by hydroxide ion. Displacement may occur by nucleophilic substitution at the phosphorus atom or at the carbon attached to the phosphate group. Attack of hydroxide also may occur at the terminal carbon atom by an S_N2' process. Any choice between these possibilities must await the results of isotopic labeling experiments.

The cyclic five-membered ring ester, methyl pinacol phosphate, was found to solvolyze in alkaline solution at an extremely fast rate, which is common in phosphate esters of this structural type. The products of the alkaline hydrolysis were both ring-opened (≈ 80%) and ring-retained (≈ 20%) diesters, whereas, in initially neutral solution, the only observed product was the ring-retained diester acid.

The bond lengths and bond angles found for methyl pinacol phosphate in the X-ray structure determination of this ester were in very close agreement to the values of the common bond lengths and bond angles in methyl ethylene phosphate. The most significant difference was found in the placement of the methyl ester groups with respect to the remainder of the molecule. In methyl ethylene phosphate, the methyl ester group is centered over the ring portion of this molecule, whereas, in methyl pinacol phosphate, the methyl ester group occupies a position nearly 180° away from the position in methyl ethylene phosphate and is almost directly over the phosphoryl oxygen atom. This result was interpreted as an important clue to and experimental verification of the nature of $d\pi$-$p\pi$ bonding in phosphate esters.

By examination of the known structures of phosphate di- and triesters, it was concluded that point group C_s is the most applicable to the real situation rather than groups of higher symmetry. Application

of symmetry arguments (considering an ideal phosphate ester to possess C_s symmetry) has led to the conclusion that five-membered ring phosphate esters approach a situation in which only two $d\pi$-$p\pi$ bonds to the alkoxy substituents are possible, whereas, other phosphate esters not containing the five-membered ring approach an arrangement which allows three $d\pi$-$p\pi$ bonds. The decreased $d\pi$-$p\pi$ bonding in five-membered ring esters, in addition to ring strain, is thus suggested as a very probable factor in the large rate acceleration in these esters.

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